Enclosure 2

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GE Hitachi Nuclear Energy, "ESBWR Steam Dryer Structural Evaluation," NEDO-33313, Rev. 5, Class I (Non-Proprietary), December 2013

Public Version

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GE Hitachi Nuclear Energy

NEDO-33313
Revision 5
December 2013

Non-Proprietary Information-Class I (Public)

Engineering Report

ESBWR STEAM DRYER STRUCTURAL EVALUATION

INFORMATION NOTICE

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SUMMARY OF CHANGES

NEDE-33313, Revision 5

Section	Description of Change
1.0	Section modified to clarify the overall steam dryer methodology application process, including phases for initial design, as-built, power ascension and monitoring and treatment of subsequent plants.
4.0	Added "thinner of two".
4.1	Revised discussion of FIV load definition.
4.2	Section added to clarify the application of Fatigue Strength Reduction Factors (FSRF), use and restrictions on methods to apply the FSRFs and to provide additional details on the evaluation of critical flaw sizes.
4.3	Clarified basis for weld quality factors.
Table 4.1	Revised factors included in Service Level A and B stress limits.
Figure 4-1	Clarified figure to specify the Method used to apply FSRFs.
Figure 4-2	Added figure to clarify weld joint geometric nomenclature.
5.1	Revised section to describe the three methods for enforcing rotational compatibility.
5.1.1	Revised discussion on global finite element model (FEM) convergence to describe the different methods for determining a converged model and stress convergence bias.
5.1.2	Revised discussion of FE submodel convergence.
5.1.3	Provided guidance on evaluating the results of dynamic response testing of the as-built steam dryer and disposition of differences of greater than 10% between predicted resonance frequencies and those measured during the dryer dynamic testing.
5.2.1	Revised section to describe steam dryer flow-induced vibration (FIV) loads for the design basis analysis.
5.2.2	Added new section to describe steam dryer FIV loads developed during power ascension testing.
5.2.3	Added new section to describe steam dryer FIV loads developed at the full power condition following completion of power ascension testing.
5.3	Added text to point to Table 5.1 for ASME load combinations.
Table 5.1	Formerly Table 8.1.
Figure 5-5	Added new figure to provide example of application of embedded shell elements in solid to shell transition modeling.

Section	Description of Change
Figure 5-6	Added new figure to provide example of application of overlaid shell elements in solid to shell transition modeling.
Figure 5-7	Added new figure to provide example of application of constraint equations in solid to shell transition modeling.
Figure 5-8	Added new figure to provide example of FEM convergence case with the global model mesh converged.
Figure 5-9	Added new figure to provide example of FEM convergence case with the mesh converged in refinement study.
Figure 5-10	Added new figure to provide example of FEM convergence case using extrapolation method.
6.3	Revised Section 6.3 to include a summary of the adjustments that are applied to the predicted FEM structural response.
6.3.1	Expanded the discussion on application of the methodology bias and uncertainty to clarify the application of end-to-end and load definition bias and uncertainty.
6.3.2	Added new section to summarize the use of the bias and uncertainty of the FEM obtained from dynamic response testing.
6.3.3	Added new section to summarize the application of FSRFs.
6.3.4	Added new section to summarize the application of stress convergence bias errors.
6.3.5	Clarified discussion on combining peak stress from low frequency and high frequency analyses to distinguish between dependent and independent combination of terms.
6.3.6	Created new subsection for "Bias and Uncertainty and Benchmarking Using Harmonic FE FIV Solution".
6.3.7	Added new section to describe application of trending factors to project steam dryer structural response at different power levels.
6.3.8	Added new section to describe components and application of instrument bias and uncertainty.
Table 6.1	Formerly Table 5.2.
7.0	Revised section to clarify application of adjustment factors to the predicted structural response.
7.1	Revised section to clarify application of adjustment factors to the predicted structural response for the design basis analysis.
7.2	Added new section and clarified application of adjustment factors to the predicted structural response for the as-built analysis.

Section	Description of Change
7.3	Added new section and clarified application of adjustment factors to the predicted structural response during the power ascension testing.
7.4	Added new section and clarified application of adjustment factors to the predicted structural response for final post-startup confirmation analysis.
Table 7.1	Revised previous now Table 7.1 to provide additional description of adjustment factors applied to the predicted steam dryer structural response for the four analysis types.
Figure 7-1	Deleted Figure 7-1 and associated text in Section 7.
8.2	Clarified application of peak stress intensities for primary membrane and primary bending stress evaluations.
9.2	Revised description of the instrument bias and uncertainty and clarified application of instrument bias and uncertainty when determining startup testing acceptance criteria.
9.2	Deleted discussion of the "Uncertainty Assessment Method" for determining startup testing acceptance criteria since it is not used.
9.2	Clarified in steps 3 and 4 how the startup acceptance criteria are calculated for the Minimum Load Case methodology.
10.0	Added explanation regarding new Appendix A and Appendix B.
10.1.1	Added new section to address the required contents of a steam dryer design analysis report.
10.1.2	Added new section to address the required contents of a steam dryer as-built analysis report.
10.1.3	Created new subsection for "Confirmatory Stress Analysis".
10.2	Revised Section 10.2 to indicate that the wording of license conditions or regulatory commitments in a COLA may be different from the wording included in the engineering report. Modified Section 10.2 for addressing COL Information Item 3.9.9-1-A and changed the subheading for 10.2(a).
10.2.a	Revised the section to delete information that provided details on the RG 1.20 regulatory positions and added requirements for the content of a Steam Dryer Monitoring Program.
10.2.b	Added "See Section 10.1.1 above for more details on how the COL applicant would address this item in a COL application."
10.2.c	Revised Section 10.2.c to indicate that the wording of license conditions in a COLA may be different from the wording included in the engineering report.
10.2.c, Item 1	Revised section to define content of Power Ascension Test procedures.

Section	Description of Change
10.2.c, Item 2	Revised section to describe requirements that must be satisfied during the Power Ascension testing at the initial hold point.
10.2.c, Item 3	Revised section to describe requirements that must be satisfied during the Power Ascension testing at subsequent hold points.
10.2.c, Items 4-9	Revised section to describe additional requirements that must be satisfied during Power Ascension testing and after full power has been achieved.
10.2.d	Revised section to clarify requirements for periodic steam dryer inspections during refueling outages.
11.0	Deleted "Method 1" after "PBLE01".
12.0	Updated revision levels and dates for References 6 and 11.
Appendix A	Added new appendix to discuss requirements to satisfy ITAAC 8.b.
Appendix B	Added new appendix to discuss requirements to satisfy ITAAC 36.

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ACRONYMS AND ABBREVIATIONS

Term	Definition
ABWR	Advanced Boiling Water Reactor
ASME	American Society of Mechanical Engineers
ATWS	Anticipated Transient Without Scram
BWR	Boiling Water Reactor
COL	Combined Operating License
DCD	Design Control Document
DP	Differential Pressure
DW	Dead Weight
ESBWR	Economic Simplified Boiling Water Reactor
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Model
FIV	Flow Induced Vibration
FSAR	Final Safety Analysis Report
FSRF	Fatigue Strength Reduction Factor
GEH	GE Hitachi Nuclear Energy
GGNS	Grand Gulf Nuclear Station
HF	High Frequency
IOT	Infrequent Operating Transient
LBL	Large Break LOCA
LOCA	Loss-of-Coolant Accident
LF	Low Frequency
MASR	Minimum Alternating Stress Ratio
PAT	Power Ascension Test
MSLB	Main Steam Line Break
PBLE	Plant Based Load Evaluation
PS	Power Spectrum
PSD	Power Spectral Density
RG	Regulatory Guide
RMS	Root Mean Square
RPV	Reactor Pressure Vessel
SBL	Small Break LOCA
SOT	System Operating Transient
SRSS	Square Root Sum of the Squares

Term	Definition
SRV	Safety Relief Valve
SSE	Safe Shutdown Earthquake
SSES	Susquehanna Steam Electric Station
TSV	Turbine Stop Valve
VY	Vermont Yankee

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 (Reference 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,

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

The approach used for the Economic Simplified Boiling Water Reactor (ESBWR) steam dryer structural evaluation includes the following:

I. Design

1. Maintain key aspects of the Advanced Boiling Water Reactor (ABWR) steam dryer and steam plenum region geometries that have provided satisfactory performance with similar rated steam flow, reactor size, and steam outlet nozzle configuration.

2. Evaluate the expected acoustic response of the reactor steam dome and main steam system in order to avoid or eliminate geometries that can result in large acoustic loads.

3. Analyze the steam dryer design with independent sets of design loads that include high amplitude loads covering a wide frequency spectrum. These design loads are developed from instrumented plant steam dryer data using the Plant Based Load Evaluation (PBLE01) methodology. End-to-end bias and uncertainty developed from Grand Gulf Nuclear Station (GGNS) steam dryer data is applied to the design basis, but without credit for positive bias that works in the direction of reduced fatigue margin. For ESBWR, the projected load definitions bound the ABWR test data when extrapolated [[

]]

4. Demonstrate that the fatigue analysis results for the as-designed steam dryer maximum calculated alternating stress intensity meet or exceed a Minimum Alternating Stress Ratio [MASR] of 2.0 to the allowable alternating stress intensity of 93.7 MPa (13,600 psi).

5. Demonstrate that the primary stress results for the as-designed steam dryer meet the acceptance criteria for the normal, upset, emergency, and faulted load combinations.

II. As-built Steam Dryer

1. Address any changes between the as-designed and as-built steam dryer.
2. Perform dynamic testing, "frequency response testing", of the fabricated steam dryer to compare the predicted versus measured frequency response. Define the finite element model (FEM) bias and uncertainty [[ ]] based on the results of the comparison. Recalculate stress using the FEM bias and uncertainty based on the frequency response test.
3. Verify that the fatigue analysis results for the as-built steam dryer maximum calculated alternating stress intensity will meet or exceed an MASR of 2.0 to the allowable alternating stress intensity of 93.7 MPa (13,600 psi).
4. Verify that the primary stress results for the as-built steam dryer meet the acceptance criteria for the normal, upset, emergency, and faulted load combinations.
5. Identify on-dryer instrumentation sensor specifications, sensor locations, correlations between sensors and peak stress locations, and bias and uncertainties of sensors and data acquisition system.
6. Define steam dryer instrument acceptance limits that maintain peak alternating stress amplitude less than 93.7 MPa (13,600 psi) for the steam dryer. Limit curves for power ascension will be based on the worst-case of the design basis calculations that use the end-to-end GGNS bias and uncertainty, and those from the as-built steam dryer calculations that use the combined FE structural and PBLE01 biases and uncertainties.

III. Power Ascension Monitoring and Inspection

1. Develop a steam dryer power ascension monitoring and inspection program that reflects industry experience with the performance of steam dryer power ascension testing.
2. Instrument and monitor the steam dryer during power ascension to measure steam dryer pressure loads as well as steam dryer strain and acceleration to assure that adequate steam dryer fatigue margin is maintained.
3. At approximately 75% power during the initial power ascension, perform the following:
    a. Record pressures, strains, and accelerations from the on-dryer mounted instrumentation. Evaluate the data and compare the measured dryer strains and accelerations to acceptance limits.
    b. Develop a PBLE01-based ESBWR flow-induced vibration (FIV) load definition based on selected on-dryer instruments. Using appropriate methods, such as F-Factor and Root Mean Square (RMS), and the

above PBLE01-based ESBWR load definition, predict the steam dryer strain and acceleration response at this condition.

c. Compare the predicted steam dryer strain and acceleration against the measured data and determine frequency dependent end-to-end bias and uncertainty values. Adjust the predicted strain and acceleration responses using the frequency-dependent end-to-end bias errors and uncertainty values. If any of the measured sensor data exceed the adjusted predictions, then either modify the bias errors and uncertainty values and limit curves and ensure measured sensor responses do not exceed the adjusted predictions, or quantitatively evaluate the impact on fatigue life.

d. Define the steam dryer peak stress projections based on the revised results from step III.3.b with modified end-to-end bias and uncertainties from step III.3.c. Compute the steam dryer maximum stress and minimum stress ratio from the predictive analysis using up to a [[ ]] applications. Prepare cumulative stress plots for at least the [[ ]] most highly stressed locations on both the upper and lower dryer with the dominant stress component at each location used for the plots. The peak stress amplitude adjusted for the bias and uncertainty is maintained less than 93.7 MPa (13,600 psi).

e. Update limit curves based on the results from step III.3.d. Level 1 and Level 2 limit curves will be generated for all functioning strain gage and accelerometer locations on the steam dryer and will include bias errors and uncertainties as described in Section 7.

f. Trend the recorded data and project the stress, strain and accelerometer sensor responses for the next assessment point and full power to demonstrate margin for continued power ascension.

4. Continue power ascension in no more than 5% power increments up to 100% power in accordance with the power ascension monitoring plan. Appropriate methods, such as F-Factor and RMS, will be used to monitor dryer stresses at intermediate power levels during power ascension.

5. During power ascension, if flow-induced resonances are identified and the strains or vibrations increase above the pre-determined criteria, power ascension is stopped. The acceptability of the steam dryer for continued operation is evaluated [[ ]]. The limit curves are then redefined based on the on-dryer data. The limit curve factor is revised [[

]]

6. When full power is obtained, the steam dryer peak stress projections are determined based on the full power test data and adjusted for end-to-end benchmark bias and uncertainties and instrument uncertainties, to demonstrate that the steam dryer will maintain its structural integrity over its design life considering variations in plant parameters (such as reactor pressure and core flow rate).
7. Conduct steam dryer inspections during the first two refueling outages and develop a long-term steam dryer inspection program based on the results of those steam dryer inspections.

IV. Subsequent Plants

Power ascension testing of subsequent plants will follow the same FIV monitoring process using on-dryer instruments incorporating lessons learned from power ascension of previous ESBWR plants as applicable. The power ascension acceptance limits for subsequent plants are based on assuring that the stresses remain less than 93.7 MPa (13,600 psi). Limits are based on frequency domain curves developed from the initial unit test data factored by a limit curve factor. The limit curve factor is determined [[

]]

The overall structural evaluation and power ascension testing for the ESBWR steam dryer is presented in this report. At this point the load definition and detailed steam dryer design are not finalized, as they depend heavily on ongoing industry and regulatory interaction. Because the stress analysis depends directly on these inputs, this report only includes a description of the analysis approach and design criteria. A detailed FEM is used to perform the structural dynamic analyses in order to predict the steam dryer's susceptibility to fatigue under FIV during normal operation. The same FEM will be used to predict the stresses resulting from specified American Society of Mechanical Engineers (ASME) load combinations. When full power is obtained, the results of these analyses are confirmed by updating the projected peak stress projections using the full power test data. The overall finite element stress analyses are supported by NEDE-33312P, which describes the development of the ESBWR steam dryer design load definition for the FIV analyses, and NEDE-33408P, which describes the PBLE01 acoustic load definition methodology. NEDE-33408P also provides an example implementation of the FIV analysis methodology.

2.0 STEAM DRYER DESIGN

2.1 Physical Description

The ESBWR steam dryer consists of a center support ring with dryer banks on top and a skirt below to make up the steam dryer assembly. A typical steam dryer is shown in Figure 2-1. The steam dryer units, made up of steam drying vanes and perforated plates, are arranged in six parallel rows called dryer banks. The upper support ring is supported by reactor pressure vessel (RPV) support brackets. The steam dryer assembly does not physically connect to the chimney head and steam separator assembly. The cylindrical skirt attaches to the support ring and projects downward to form a water seal around the array of steam separators. Normal operating water level, approximately mid-height on the steam dryer skirt, is provided as input to the analysis.

During normal refueling outages, the ESBWR steam dryer is supported from the floor of the equipment pool by the lower support ring that is located at the bottom edge of the skirt. The steam dryer is installed and removed from the RPV by the reactor building overhead crane. A steam dryer lifting device, which attaches to four steam dryer lifting rod eyes, is used for lifting the steam dryer. Guide rods in the RPV are used to aid steam dryer installation and removal. Upper and lower guides on the steam dryer assembly are used to interface with the guide rods.

2.2 ESBWR Plant Operating Conditions For Steam Dryer Design Basis Analyses

This section defines the plant operating conditions that will be assumed for the ESBWR steam dryer design basis analyses. The relevant plant parameters that determine the operating conditions for the steam dryer structural analyses are the reactor power, the reactor vessel pressure, the reactor vessel water level and reactor core flow. These parameters are interrelated and have both primary and secondary effects that influence the steam dryer structural response.

The rated reactor heat balance for 100% power used for the ESBWR plant design is shown in Figure 1.1-3a of Reference 2. The defined operating range of core power as a function of feedwater temperature is shown in Figure 4.4-1 of Reference 3. The ESBWR is a natural circulation plant and there is no active control of the core flow as in forced circulation plants. The feedwater temperature is varied as a means of changing core power level without moving control rods and is used as the functional equivalent of changing power with recirculation flow in a forced circulation plant. Nominally, the core flow at full power is a single value; however, there will be some variation in the core flow due to the power distribution changes over the fuel cycle and due to the feedwater temperature variations used to control reactor power.

The ESBWR steam dryer structural analyses will assume the maximum steam generation rate at 100% rated power as shown in the rated reactor heat balance. [[

]]

The bases for the assumed operating conditions are provided in the following sections.

2.2.1 Reactor Power

The FIV and acoustic pressure loading conditions are governed by the reactor steam generation rate and steam flow velocities in the main steam system. [[

]] Figure 4.1-1 of Reference 3 shows that there is a range of feedwater temperatures over which full power operation is allowed. The steam generation rate is maximized at [[

]] Therefore, the ESBWR steam dryer structural analyses will assume the maximum steam generation rate at full rated power as shown in the rated reactor heat balance [[

]]

2.2.2 Reactor Pressure

The reactor pressure determines the steam density and, therefore, the steam flow velocities at a given steam generation rate. [[

]] This effect was observed in dryer response measurements taken during power ascension testing of an instrumented replacement steam dryer when [[

]]

The reactor pressure will vary during normal operation for two reasons: the pressure fluctuations during steady-state operation and the allowed tolerance for the pressure regulator setpoint. The pressure fluctuations during normal operation are small (typically less than ±2 psi) which will have only a small effect on the steam flow velocities and dryer pressure loading. [[

]]

There is an allowed tolerance (typically ±5 psi) in the turbine inlet pressure regulator setpoint that controls the reactor system pressure. Under normal circumstances, the pressure regulator setpoint is adjusted early in the reactor system pressurization so that the reactor will be at nominal pressure when full power is achieved and is not readjusted during the cycle. In addition, the plant thermal efficiency (electrical generation as a function of thermal power) is maximized by operating the reactor system at the high end of the allowable pressure range, which, [[

]] The pressure setpoint readjustment during that plant's final EPU power ascension was unusual and was the result of the mid-cycle EPU license amendment approval and implementation. It is not likely that the ESBWR will be operated at full power at lower reactor system pressures for any longer than would be necessary.

[[

]] Therefore, consideration of a [[

]]

2.2.3 RPV Water Level

The RPV water level [[

]] Similar to the reactor pressure, the vessel water level will vary during normal operation for two reasons: the level fluctuations during steady-state operation and the allowed tolerance for the level controller setpoint. [[

]]

2.2.4 Reactor Core Flow

Power ascension testing of an instrumented replacement steam dryer showed [[

]]

The ESBWR is a natural circulation plant and there is no active control of the core flow as in forced circulation plants. Nominally, the core flow at full power is a single value; however, there will be some variation in the core flow due to the power distribution changes over the fuel cycle and due to the feedwater temperature variations used to control reactor power. The effects of those core flow variations on the steam dryer structural response are discussed below.

2.2.4.1 Core Flow Variation over the Fuel Cycle

The rated reactor heat balance for 100% power (Figure 1.1-3a in Reference 2) provides a core flow range of 31,553 to 37,352 t/hr or ±8.4% of the nominal core flow 34,452 t/hr (the average of 31,553 and 37,352). This range considers both the uncertainties in the predicted core flow and the effect of core exposure over the cycle. Table 2.2-1 of Reference 4 provides an example of the nominal core flow variation over the fuel cycle at rated power and feedwater conditions (i.e., constant steam flow). The core flow varied from a low of 35,042 t/hr to 36,144 t/hr or approximately 3%. Therefore, most of the core flow range shown on Figure 1.1-3a of Reference 2 reflects the uncertainty in the core flow prediction. The difference between the nominal core flow in the design heat balance and the maximum core flow in Table 2.2-1of Reference 4 is 4.9%. For comparison, the full power core flow window for the forced circulation plant where the core flow effect was observed on the instrumented dryer is about 12%. The ESBWR core flow window of 3-5% is much smaller than the 12% window for a typical forced circulation plant. Therefore, [[

]]

2.2.4.2 Core Power/Feedwater Temperature Operating Map

The ESBWR core flow will also vary as the final feedwater temperature is varied. The feedwater temperature is varied as a means of changing core power level without moving control rods and is used as the functional equivalent of changing power with recirculation flow in a forced circulation plant. The defined operating range of core power as a function of feedwater temperature is shown in Figure 4.4-1 of Reference 2. The reactor heat balance conditions for the feedwater temperature operating range are provided in Reference 5 (Figure 2.1-1, Figure 3.1-1, and Table 3.2-1).

The dryer stresses are expected to [[

]] As described in Section 10.2, the final dryer stress analysis predictions will be benchmarked at full power operation against on-dryer measurements taken over the range of steady state plant operating conditions during the prototype plant startup.

[[

]]

Figure 2-1. Typical Steam Dryer Installed in RPV

3.0 MATERIAL PROPERTIES

The steam dryer will be manufactured from low carbon wrought 300 series stainless steel and Grade CF3 stainless steel castings conforming to the requirements of GE Hitachi Nuclear Energy (GEH) material and fabrication specifications. Specific material properties at operating temperature will be taken from Reference 7.

4.0 DESIGN CRITERIA

The steam dryer, including the dryer units, is a non-safety related item and is classified as an Internal Structure per Reference 8, as defined in Reference 9, Subsection NG, Paragraph NG-1122. The steam dryer is not an ASME Code component, but the design shall comply to the applicable requirements of ASME Code Subsection NG-3000 for primary structural welds. For [[

]].

4.1 Fatigue Criteria

The steam dryer fatigue evaluation consists of calculating the alternating stress intensity from FIV loading at all locations in the steam dryer structure and comparing it with the allowable design fatigue threshold stress intensity requirements from Reference 10. [[

]]

4.2 Fatigue Strength Reduction Factors

[[

]]

4.3 Weld Quality Factor

For the case of the steam dryer, which is not a core support structure, it was [[

]]

4.4 ASME Code Stress Limits for Load Combinations

The ASME Code stress limits from Subsection NG of Reference 9 are listed in Table 4.1.

Table 4.1 ASME Code Stress Limits

Service Level	Stress Category	Core Support Structures Stress limits (NG)
Service Levels A&B	P_m	S_m
	$P_m + P_b$	$1.5S_m$
	$P_m + P_b + Q$	$3.0S_m$
	$P_m + P_b + Q + F$	S_a
Service Levels C	P_m	$1.5S_m$
	$P_m + P_b$	$2.25S_m$
Service level D	P_m	Min($0.7S_u$ or $2.4\ S_m$)
	$P_m + P_b$	1.5(P_m Allowable)

Legend:

P_m:General primary membrane stress intensity
P_b:Primary bending stress intensity
*Q:*Secondary stress
F:Peak stress
S_m:ASME Code Design Stress Intensity
S_a:Allowable stress intensity
S_u:Ultimate strength

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

[[ ]]

Figure 4-1. Fatigue Strength Reduction Factor Flow Diagram

[[ ]]

Figure 4-2. Schematic of Weld Joint Showing Geometric Nomenclature

5.0 STEAM DRYER FE MODEL AND APPLIED LOADS

5.1 Full Steam Dryer Shell Finite Element Model

[[

]]

5.1.1 Global FE Model Convergence

[[

]]

5.1.2 FE Submodel Convergence

[[

]]

5.1.3 Dynamic Testing

On a new plant where there is more time and space to accommodate frequency response testing, shaker testing may be used in lieu of hammer testing. Either a hammer or a shaker with a force transducer will provide the excitation.

[[

]] For each test, input force, accelerations, transfer functions, coherence at all accelerometers are measured. Multiple excitation locations are used. The transfer functions for each measurement location are calculated. [[

]]

5.2 Dynamic Pressure Loads

5.2.1 Design Basis FIV Loads

[[

]] The design basis FIV loading time history and any necessary loading scale factors are taken from Reference 6. [[

]]

5.2.2 ESBWR Power Ascension FIV Loads

During power ascension, the pressure loading on the face of the steam dryer will be measured [[ ]] Using the PBLE01 methodology described in Reference 11, [[ ]] These loads will be used to adjust the predicted structural model responses [[ ]] Sections 6 and 7 provide additional details on the application of bias and uncertainty.

5.2.3 ESBWR Full Power FIV Loads

Following completion of the power ascension program, a set of full power ESBWR-specific FIV loads will be developed [[ ]] The loads will be generated using the PBLE01 methodology described in Reference 11. These full power loads will be used to perform a structural evaluation [[ ]] will be applied to the structural model predictions to determine the final peak stress values for the ESBWR steam dryer at full power conditions. Sections 6 and 7 provide additional details on the application of bias and uncertainty.

5.3 ASME Loads

Table 5.1 provides the load combinations and describes the load cases to be used in the ASME load combinations stress analysis

Table 5.1 ASME Load Combinations and Conditions

Service Level	Plant Events	Load Combination	Note
A	N	$DW + DPn \pm FIVn+L_T+C$	
B	Plant/System Operating Transients (SOT)	$DW + DPn \pm FIVn +L_T+C +SRV$	
		$DW + DPn\pm FIVn+ L_T+C + TSV1$	4
		$DW + DPn+ L_T+C + TSV2$	2
C	Infrequent Operating Transient (IOT), ATWS	$DW + DPn \pm FIVn+ L_T+C +SRV$	5
D	LOCA (SBL)	$DW + DPn \pm FIVn+ L_T+C +[HVL^2+CHG^2+SRV^2]^{1/2}$	5
D	LOCA (SBL) + SSE	$DW + DPn \pm FIVn+ L_T+C +[HVL^2+CHG^2+SRV^2+ SSE^2]^{1/2}$	5
D	LOCA(LBL) + SSE	$DW + DPn + L_T+C + [SSE^2 + AC1^2 + FIVn^2]^{1/2}$	1
		$DW+ L_T+C + [DPf1^2 + SSE^2]^{1/2}$	3

Notes:

1. Loads from independent dynamic events are combined by the square root sum of the squares method.
2. In the listed B combination, FIVn is not included because the reverse flow through the steamlines will disrupt the acoustic sources that dominate the FIVn load component.
3. In the listed D combinations, FIVn is not included because the level swell in the annulus between the steam dryer and vessel wall will disrupt the acoustic sources that dominate the FIVn load component.
4. For bearing stress assessment only, the square root of the sum of the squares method may be used to combine TSV1 and FIVn (load combination B).
5. The most limiting load combination case among SRV(1), SRV(2), and SRV(ADS).

Definition of Load Acronyms

AC1 Acoustic load due to main steam line break (MSLB) outside containment, at the Rated Power and Core Flow (Hi-Power) Condition.

C Constraint from internals

CHG Chugging loads

DW Dead Weight.

DPn Differential 'static' Pressure Load During Normal Operation.

DPfl	Differential Pressure Load in the Faulted condition, due to MSLB outside containment at the Rated Power and Core Flow (Hi-Power) condition.
FIVn	Flow Induced Vibration Load during Normal Operation.
HVL	Horizontal Vent Chugging loads
LBL	Large Break LOCA Loads
L_T	Temperature effect
SBL	Small Break LOCA Loads
SRV	Safety Relief Valve
SSE	Safe Shutdown Earthquake.
TSV1	The Initial Acoustic Component of the Turbine Stop Valve (TSV) Closure Load. (Inward load on the outermost hood closest to the nozzle)
TSV2	The Flow Impingement Component (following the Acoustic phase) of the TSV Closure Load; (Inward load on the outermost hood closest to the nozzle)

[[

]]

Figure 5-1. Typical Finite Element Model

[[

]]

Figure 5-2. Typical Dryer Structural FEM Showing Components

[[

]]

Note: Different Colors represent Different Components

Figure 5-3. Typical Tee Bar, Skirt, Drain Channels, Drain Pipes, Lower Support Ring

[[

]]

Figure 5-4. Typical Boundary Conditions on Structure

[[ ]]

Figure 5-5. Solid to Shell Transition – [[ ]]

[[ ]]

Figure 5-6. Solid to Shell Transition – [[ ]]

[[ ]]

Figure 5-7. Solid to Shell Transition – [[ ]]

[[ ]]

Figure 5-8. Global Model Mesh Converged

[[ ]]

Figure 5-9. Mesh Convergence in Refinement Study

[[ ]]

Figure 5-10. Mesh Convergence by Extrapolation Method

6.0 VIBRATION ANALYSIS AND PREDICTED COMPONENT STRESSES

6.1 Approach

The ANSYS FE code will be used to obtain the structural responses of the steam dryer to the FIV loads at operating temperature. The dynamic analysis will be performed [[ ]]

6.2 Stress Recovery

The maximum stress intensity [[ ]]

If warranted by initial analysis, additional analysis will be performed to further refine the stress prediction. [[ ]]

6.3 Adjustments to the Steam Dryer FIV Stress

To provide an adequately bounding stress analysis and to account for uncertainties in the overall methodology, a series of bias and uncertainties and adjustments are applied to the predicted peak stress. The following sections summarize the various bias and uncertainties and other adjustment factors. Section 7 defines how these values are applied to the dryer structural response to determine the sensor response and peak stress.

6.3.1 Methodology Bias and Uncertainty

Reference 11 describes the FIV load and end-to-end benchmarking process used to establish the bias and uncertainty values for the steam dryer FIV load and stress analysis and also provides an example implementation of the methodology. Appendix J of Reference 11 provides [[ ]] and Appendix F of Reference 11 provides the [[

]]

6.3.2 FE Model Bias and Uncertainty (Section 5.1.3)

[[

]]

6.3.3 Fatigue Strength Reduction Factors (Section 4.1)

[[

]]

6.3.4 Stress Convergence Bias (Sections 5.1.1 and 5.1.2)

[[

]]

6.3.5 Period of Peak Response for FIV Assessment

The FIV loading used in the FE stress analysis considers highest stress intensities that occur at frequencies as low as approximately 1 cycle per 100 seconds. [[

]]

In the F-Factor method, [[

]]

Assume that [[

]]

The BiasFactor in Equation (7) is a [[

]]

The [[

]]

Therefore, it is assumed the same relation follows [[

]]

The [[

]]

As with the F-factor method, the acoustic and structural model is linear and therefore a [[

]]

6.3.6 Bias and Uncertainty and Benchmarking Using Harmonic FE FIV Solution

[[

]]

6.3.7 Trending Factor

To project the predicted structural response to 100% power (or other intermediate power plateaus), [[ ]] As a function of frequency band, [[

]]

6.3.8 Instrument Bias and Uncertainty

The instrumentation bias and uncertainty is accounted for in the methodology when comparing predictions to measured values and also when establishing limits. The instrumentation bias and uncertainty addresses the overall accuracy of the total measurement system which includes [[

]] Instrumentation bias and uncertainty is determined [[

]]

Each sensor signal goes through several devices, so for a given sensor sensitivity, [[

]] For strain gages, additional factors are included in the overall measurement accuracy [[
]]

The overall random signal conditioning devices uncertainty based on specified accuracies of the electronic devices [[ ]] This error does not include [[
]]

Table 6.1

Time Domain Strain Gage Data Statistics

[[

]]

7.0 FATIGUE PREDICTION

[[

]] These stresses will then be compared to the criteria from Section 4.1.

[[

]]

7.1 Analysis 1 – Design Basis Analysis

[[

]]

In the design basis analysis (Section 1 of Table 7.1), credit for potential [[

]]

7.2 Analysis 2 – As-built Confirmatory Analysis

[[

]]

7.3 Analysis 3 – Power Ascension Confirmatory Analysis

[[

]]

7.4 Analysis 4 – Post Startup Confirmation Analysis

[[

]]

Table 7.1 ESBWR Steam Dryer Analyses

[[ ]]

Figure 7-1. [Deleted]

8.0 ASME LOAD COMBINATIONS

8.1 ASME Approach

The structural responses of the steam dryer to the ASME load combinations will be evaluated using the ANSYS FE code and loading from Section 5.3. [[
]]

8.2 ASME Load Case Stress Results

[[

]] These stresses will then be compared to the criteria from Section 4.4.

9.0 STARTUP TEST DESIGN AND ANALYSIS

9.1 Instrumentation for Monitoring Steam Dryer Response

The ESBWR steam dryer is instrumented with temporary vibration sensors to obtain FIV data during power operation. The primary function of this vibration measurement program is to verify that the steam dryer can adequately withstand stresses from FIV forces for the design life of the steam dryer. Strain gages and accelerometers are used to monitor the structural response during power ascension and to validate the fatigue stress predictions in Section 7.0 for normal operation. Accelerometers are also used to identify potential rocking and to measure the accelerations resulting from support and vessel movements.

[[

]]

In addition [[

]]

9.2 Startup Testing Acceptance Criteria

The structural analysis performed for the steam dryer design consists of a dynamic FEA. To address the uncertainty in the structural natural frequencies, the load definition frequencies are varied over a range of ±10% of nominal in 2.5% steps (nine cases total).

Similar to Subsection 3L.5.5.2, Step 5, for one-dimensional (uni-axial) structural responses and with the strain gage located at the maximum stress location in the steam dryer, the determination of strain measurement acceptance criteria would be:

$$\varepsilon = \sigma / (E)$$

where

σ = highest stress intensity allowable limit

E = Young's Modulus, 1.78×10^5 MPa (25.8×10^6 psi) at 288°C (550°F) for steam dryer material.

With a highest stress intensity allowable limit of 93.7 MPa (13,600 psi), the strain acceptance limit with the strain gage at the maximum stress location, is calculated as follows:

$\varepsilon = \sigma/(E) = 527\ \mu\varepsilon$ (zero-peak) or $1054\ \mu\varepsilon$ (peak-peak)

[[

]]

10.0 COMPREHENSIVE VIBRATION ASSESSMENT PROGRAM FOR THE ESBWR STEAM DRYER

The series of steps outlined in Section 1.0 describe the high level analysis and test related tasks that represent the GEH implementation of Regulatory Guide (RG) 1.20 requirements for the ESBWR steam dryer. The focus of this report is the structural FIV analysis and test (i.e., measurement) requirements, which make up two of the three main elements of the comprehensive vibration assessment program described in the guide (the third element is inspection). This section describes the RG requirements as they relate to the ESBWR steam dryer and DCD.

In addition, for certain related actions that will be taken after a COL is issued, the process and reporting for demonstrating ITAAC acceptance criteria are met are discussed in Appendix A, "ITAAC For Reactor Pressure Vessel and Internals," and Appendix B, "ITAAC for Main Steam Line and SRV/Safety Valve Branch Piping Acoustic Resonance."

10.1 ESBWR Steam Dryer Prototype Design Basis and Analysis Reports

The ESBWR steam dryer is a prototype steam dryer under the guidance in NRC RG 1.20. Section C1.1 of the regulatory guide defines "prototype" as a "configuration of a reactor internal that, because of its arrangement, design, size, or operating conditions, represents a first-of-a-kind or unique design for no 'valid prototype' exists." Because the ESBWR steam dryer is considered a prototype in the design certification, each subsequent ESBWR steam dryer will also be considered a prototype. Only if the design certification is amended or future Combined License Applicants or Licensees seek NRC approval of a departure and exemption from the design certification requirements on a plant-specific basis would subsequent ESBWR steam dryers be considered non-prototypes under the provisions of RG 1.20.

As discussed in Section 1.0, each ESBWR steam dryer is subject to predictive analyses and verification through instrumentation during power ascension at initial startup, with acceptance limits of 93.7 MPa (13,600 psi). For additional conservatism in the design basis predictive analysis, the analysis stress results will meet a MASR of 2.0 between the analysis results and the fatigue acceptance limit. The design basis analysis is validated for each as-built steam dryer through inspections, tests, analyses and acceptance criteria (ITAAC) during construction of the plant for the specific steam dryer that is to be installed in the RPV. The startup testing then uses the fatigue limit stress amplitude of 93.7 MPa (13,600 psi) with a MASR of 1.0 as the basis for acceptance limits for the on-dryer instrument measurements during power ascension. A confirmatory stress analysis is performed based on the on-dryer measurements following startup testing.

10.1.1 Steam Dryer Design Analysis Report

A Combined License applicant will address COL Information Item 3.9.9-1-A for a prototype dryer. NRC Regulatory Guide 1.206, Section C.I.3.9.2.4, states that, for a prototype reactor, "if the FIV testing of reactor internals is incomplete at the time the COL application is filed, the applicant should provide documentation describing the implementation program, including milestones, completion dates and expected conclusions." If the ESBWR steam dryer has been subjected to flow-induced vibration, then there will be information on the design of the dryer that would be included in the description of the steam dryer.

For the initial ESBWR steam dryer, an example of a steam dryer that has been subjected to the flow induced vibration testing is presented in NEDE-33408, with detailed information obtained through the design, analysis, and testing of an extended power uprate replacement steam dryer for the Grand Gulf Nuclear Station (GGNS). The process that was employed for the GGNS replacement steam dryer will be employed for the ESBWR steam dryer, including the Power Ascension Test Program described in Section 10.2.

A COL applicant will prepare an as-designed ESBWR steam dryer analysis report that will address the items below. A COL applicant for an initial ESBWR steam dryer design may not have all of the items below prior to issuance of the COL. In that case, the COL applicant should follow the process in NRC Regulatory Guide 1.206 to provide sufficient information for licensing and propose appropriate post-licensing commitments (e.g., ITAAC) to confirm the acceptability of the steam dryer design. The elements that are to be included in a Steam Dryer Design Analysis Report are as follows:

a. Describe the as-designed ESBWR dryer, dryer loading, and dryer stress analysis results.
b. Reference previously approved methodology in the ESBWR DCD and Engineering Reports NEDE-33408, NEDE-33312, and NEDE-33313.
c. Describe application of the bias and uncertainty as documented in the approved methodology.
d. Describe how the alternating peak stress intensities at the high stress locations were calculated (i.e., Method 1, Method 2, or Method 3 for weld locations); and tabulate the predicted alternating peak stress intensities.
e. Demonstrate final alternating stress ratios (MASRs) greater than or equal to 2.0.
f. Include spectra and cumulative stress plots for the top five stress locations on the upper dryer and the top five stress locations on the lower dryer.
g. Describe a dryer dynamic test plan including sensor and drive locations sufficient to extract important resonances, with regional frequency response functions sufficiently resolved to establish regional bias and uncertainty for frequencies up to [[ ]].
h. Incorporate lessons learned from power ascension of previous ESBWR plants, as applicable.

10.1.2 Steam Dryer As-built Analysis Report

ITAAC 16 in DCD Tier 1 Table 2.1.1-3 is for verifying that the as-built steam dryer fatigue analysis provides at least a minimum MASR of 2.0 to the allowable alternating stress intensity of 93.7 MPa (13,600 psi). The following elements are to be included in a Steam Dryer As-Built Analysis Report:

a. Describe changes between the as-designed and as-built steam dryers, including adjustments to the structural FE model, updated bias and uncertainty based on testing, and updated stresses and stress ratios.

b. Demonstrate that the as-built ESBWR steam dryer with the assumed pressure loading satisfies the methodology to calculate the resulting dryer alternative stress with at least an MASR of 2.0 as described in the DCD and its engineering reports.

c. For the dryer dynamic testing specify the minimum number of excitation locations to ensure adequate coverage of the dryer, and that enough resonances are extracted so that comparisons may be made to simulations up to [[ ]]. Specify how the dryer will be subdivided into sensor groups/regions, whether multiple excitation locations will be specified within a group/region, and how the different regional errors for different excitation locations will be addressed.

d. Address the uncertainties in the comparison of predicted mode shapes with those measured during the dryer dynamic testing (i.e., boundary conditions and dryer support).

e. Address differences of greater than [[ ]]between predicted resonance frequencies and those measured during the dryer dynamic testing to ensure worst case coupling between peak excitation and peak response is captured.

f. Identify on-dryer instrumentation sensor specifications, sensor locations (including [[ ]]) and at least [[ ]], and correlations between sensors and peak stress locations on the upper and lower dryer.

g. Identify all biases and uncertainties associated with the sensors and data acquisition system.

h. Provide the acceptance limits for each sensor with supporting calculations (spectra and time histories). The limits should extend to 1 kHz based on the potential for high frequency excitation tones. Explain how the limits are derived from calculations using the minimum load case method described in Section 9 of NEDE-33313. Limit curves for power ascension will be based on the worst case of both the design basis calculations that use the end-to-end GGNS bias and uncertainty, and those from the as-built steam dryer calculations that use the combined FE structural and PBLE01 biases and uncertainties.

i. Confirm that redundant pressure sensors will be located adjacent to each MSL inlet.

j. Describe the ESBWR steam dryer power ascension monitoring and inspection program.

10.1.3 Confirmatory Stress Analysis

For the confirmatory stress analysis, a structural assessment is performed to benchmark the FE model strain and acceleration predictions against the measured data. The dryer stresses are determined using the on-dryer based measurement FIV load definition and adjusted for end-to-end bias and uncertainties determined from the FE model benchmark. A fatigue limit stress amplitude of 93.7 MPa (13,600 psi) with a MASR of 1.0 is used as the acceptance limit for this confirmatory stress analysis.

The subsequent ESBWR steam dryers will follow the same process as the initial prototype ESBWR steam dryer, with the predictive analysis verified through inspections, tests, and analyses acceptance criteria, the FIV monitoring process using on-dryer instruments during startup testing, and a confirmatory analysis based on the on-dryer measurements at full power following startup testing. The acceptance limits for steam dryers in subsequent plants are based on (1) the predictive analysis for the as-built steam dryer satisfying the 2.0 MASR to the 93.7 MPa (13,600 psi) fatigue stress limit, and (2) assuring that the dryer stresses remain less than 93.7 MPa (13,600 psi) with a MASR of 1.0 for the startup testing and confirmatory analysis based on on-dryer measured data.

Through the DCD and supporting reports, the ESBWR dryer is defined as a prototype, so that each subsequent ESBWR steam dryer is subject to a thorough process of analysis, verification, and confirmation of its structural integrity. Assuming that the first ESBWR steam dryer subjected to the comprehensive vibration assessment program delineated in RG 1.20 is found to be acceptable, the subsequent steam dryers with the same design are still subject to confirmation through the same process. If the ESBWR steam dryer design is modified, it would also be a prototype and would be subject to the same process for the first of that design and for the subsequent plants. Similarly, if the analysis methodology or elements of the analysis methodology are modified from the benchmark approach approved as part of the design certification, the process for a new prototype would apply, but in the case of changes in the methodology, NRC approval of the methodology changes would be required.

10.2 Comprehensive Vibration Program Elements for a COL Applicant

In the ESBWR DCD, Tier 2, Section 3.9 and Section 3L.4 discuss certain aspects of the comprehensive vibration program, including power ascension monitoring and startup testing, for the steam dryer. This section supplements the DCD description of the comprehensive vibration program elements as to how the program is implemented. Some information is redundant to the DCD for completeness. This section also describes actions to be completed by the COL licensee related to the power ascension monitoring and inspection program. The following model license conditions state the key elements of the startup test program applicable to the steam dryer, which are described further in DCD Section 3L.5, but does not bind either a COL applicant or the NRC staff. A COL applicant may propose the model condition or a different condition in its application, and the NRC is free to exercise its discretion to include a license condition governing the startup test program as applied to the steam dryer in a COL that references the ESBWR design.

As stated in Section 3L.4.6, the instrumentation and startup testing program for the ESBWR steam dryer follows NRC regulatory guidance in Reference 3L-10 (NRC RG 1.20, Revision 3 [Reference 1 herein]) regarding implementation of a comprehensive vibration assessment program. The purpose of the vibration assessment program is to verify that the steam dryer can adequately withstand stresses from FIV forces for the design life of the steam dryer. Combined Operating License (COL) Information Item 3.9.9-1-A, which is included in Section 3.9.9 of the ESBWR DCD, addresses the steam dryer.

The following information discusses elements of COL Information Item 3.9.9-1-A.

(a) Describe the Comprehensive Vibration Assessment Program for the steam dryer methodology consistent with RG 1.20 and commit to providing a Steam Dryer Monitoring Plan.

NRC regulatory guidance (Reference 3L-10) describes elements of the comprehensive vibration assessment program that is implemented prior to and through startup testing.

The following regulatory positions of RG 1.20 for prototype steam dryers address the program elements applicable to the ESBWR steam dryers:

- Position 2.1 provides a description of the vibration and stress analysis program, including specific items that should be included in the vibration and stress analysis submittal prior to implementation of the vibration measurement program.
- Position 2.2 provides a description of the vibration and stress measurement program, which is to verify the structural integrity of reactor internals, determine the margin of safety, and confirm results of the vibration analysis.
- Position 2.3 describes the inspection program for inspection both prior to and following plant operation.
- Position 2.4 describes documentation of results of the program.
- Position 2.5 describes the schedule for conducting the vibration assessment program.

A Steam Dryer Monitoring Plan (SDMP) for each ESBWR steam dryer will be prepared and provided to the NRC no later than 90 days before startup of the applicable ESBWR unit. The SDMP will reflect industry experience with the performance of steam dryer power ascension testing.

The SDMP shall include the following, which shall be augmented or modified as appropriate to address industry experience:

- Criteria for comparison and evaluation of projected strain levels with data obtained from the on-dryer instrumentation.
- Acceptance limits developed for selected on-dryer strain gage and accelerometer locations.
- Tables of predicted steam dryer stresses at 100% power; strain amplitudes and power spectral densities (PSDs) at strain gage locations; predicted acceleration amplitudes and PSDs at acceleration locations; and maximum stresses and locations.
- Directions for establishing correlations between measured accelerations and strains and the corresponding maximum stresses.
- Identification of steam dryer strain gage locations for which limit curves will be developed, and criteria for selection of those locations.
- Methodology for developing projected strain levels for the next power level and for full power.

- Specific assessment points during power ascension. While completing assessment, power will remain steady to determine if any actions need to be taken or if power may ascend to the next level.
- Activities to be accomplished during assessment points.
- Details of the installation and calibration of the steam dryer interumentation with the instrumentation mounted and calibrated in accordance with the manufacturers' instructions to accurately measure the dynamic response.

(b) Submit or reference a steam dryer predicted analysis (for the plant-specific or a sample steam dryer) that concludes the steam dryer will not exceed stress limits with applicable bias and uncertainties and the minimum alternating stress ratio (MASR) of 2.0.

The COL applicant would include a reference to the demonstration of the ESBWR steam dryer structural integrity process that is described in Engineering Report NEDE-33408P (i.e., a replacement steam dryer for an extended power uprate of a BWR). Alternatively, a COL applicant could submit or reference an ESBWR steam dryer that has been subject to the predicted analysis process and successful startup ascension testing. See Section 10.1.1 above for more details on how the COL applicant would address this item in a COL application.

(c) Describe startup program (with proposed license conditions) that includes appropriate notification points during power ascension, and submittal of the completed analysis of steam dryer data within 90 days following completion of the power ascension testing and monitoring of the steam dryer.

The following key elements for developing license conditions are acceptable for implementing this element of the COL Information Item 3.9.9-1-A as it relates to the steam dryer comprehensive vibration assessment program (as noted above, the following model license conditions state the key elements of power ascension test procedures applicable to the steam dryer, but does not bind either a COL applicant or the NRC staff. A COL applicant may propose the model condition or a different condition in its application, and the NRC is free to exercise its discretion to include a license condition governing the startup test program as applied to the steam dryer in a COL that references the ESBWR design):

1. Power Ascension Test (PAT) procedures for the steam dryer testing will be provided to NRC inspectors no later than 10 days before start-up. The PAT procedures will include the following:
   - Level 1 and Level 2 acceptance limits for on-dryer strain gages, and on-dryer accelerometers to be used up to 100% power.
   - Specific hold points and their duration during 100% power ascension.
   - Activities to be accomplished during hold points.
   - Plant parameters to be monitored.
   - Actions to be taken if acceptance criteria are not satisfied.
   - Verification of the completion of commitments and planned actions.

2. The initial hold point during the first startup of each ESBWR plant will be at no more than 75 percent of full power. At this hold point:

    a. Record pressures, strains, and accelerations from the on-dryer mounted instrumentation. Evaluate the data and compare the measured dryer strains and accelerations to acceptance limits.

    b. Develop a Plant Based Load Evaluation (PBLE01)-based ESBWR flow-induced vibration (FIV) load definition based on selected on-dryer instruments. Using appropriate methods, such as F- Factor and Root Mean Square (RMS), and the above PBLE01-based ESBWR load definition, predict the steam dryer strain and acceleration response at this condition.

    c. Compare the predicted steam dryer strain and acceleration against the measured data and determine frequency dependent end-to-end bias and uncertainty values. Adjust the predicted strain and acceleration responses using the frequency-dependent end-to-end bias errors and uncertainty values. If any of the measured sensor data exceed the adjusted predictions, then either modify the bias errors and uncertainty values and limit curves and ensure measured sensor responses do not exceed the adjusted predictions, or quantitatively evaluate the impact on fatigue life.

    d. Define the steam dryer peak stress projections based on the revised results from step (b) with modified end-to-end bias and uncertainties from step (c). Compute the steam dryer maximum stress and minimum stress ratio from the predictive analysis using up to a [[ ]] applications. Prepare cumulative stress plots for at least the [[ ]] most highly stressed locations on both the upper and lower dryer with the dominant stress component at each location used for the plots. The peak stress amplitude adjusted for the bias and uncertainty is maintained less than 93.7 MPa (13,600 psi).

    e. Update limit curves based on the results from step (d). Level 1 and Level 2 limit curves will be generated for all functioning strain gage and accelerometer locations on the steam dryer and will include bias errors and uncertainties as described in the applicable engineering reports.

    f. Trend the recorded data and project the stress, strain, and accelerometer sensor responses for the next assessment point and full power to demonstrate margin for continued power ascension.

    g. Make available to the NRC the ESBWR steam dryer analysis summary, updated stress analysis results (including end-to-end bias and uncertainty), limit curves, and data projections for higher power levels.

3. Subsequent hold points will be in approximately 5 percent power level increments where pressures, strains, and accelerations will be recorded and evaluated. Data

trending and a projection of strain levels will be generated for the next hold point and full power. Data trending analysis during power ascension must assess whether the limits would be violated at higher power levels. Data trending results and revised limit curves will be made available to the NRC at each hold point.

4. Power ascension monitoring shall address expected increases in loading and fatigue damage due to variable plant conditions throughout the life of the dryer.
5. During initial power ascension, if flow-induced resonances are identified and the strains or vibrations increase above the pre-determined criteria, power ascension is stopped. The acceptability of the steam dryer for continued operation is evaluated [[ ]]. The limit curves are then redefined based on the on-dryer data. The limit curve factor is revised [[ ]]. If a Level 1 limit curve is exceeded, power will be reduced to a previous power level where Level 1 was not exceeded and a stress analysis will be performed to develop new limit curves. During initial power ascension, should a Level 2 limit curve be exceeded, or if the trending indicates that a Level 1 limit may be challenged prior to reaching the next hold point, the acceptance limits will be evaluated, and revised if appropriate.
6. End-to-end bias and uncertainties shall be determined by comparing the predicted and measured strain or acceleration on the steam dryer at each hold point to confirm the conservatism of the predicted dryer stress field. Adjust the predicted strain and acceleration responses using the frequency-dependent end-to-end bias errors and uncertainty values. If any of the measured sensor data exceed the adjusted predictions, then either modify the bias errors and uncertainty values and limit curves and ensure measured sensor responses do not exceed the adjusted predictions, or quantitatively evaluate the impact on fatigue life.
7. At the initial hold point and the hold points at approximately 85 and 95 percent power, power ascension will not proceed for at least 72 hours after making the steam dryer data analysis and results available to the NRC, unless notified by the NRC that power ascension may proceed earlier.
8. During the Power Maneuvering in the Feedwater Temperature Operating Domain testing, pressures, strains, and accelerations will be recorded from the on-dryer mounted instrumentation across the expected range of normal steady state plant operating conditions. An evaluation of the dryer structural response over the range of steady state plant operating conditions will be included in the stress analysis report described in Item 9 below.
9. After full power has been achieved, data at the full power level will be provided to the NRC within 72 hours, and a full stress analysis report and evaluation will be provided to the NRC within 90 days of reaching the full power level. The report will include the minimum stress ratio and the final dryer load definition using steam dryer instrumentation, and associated bias errors and uncertainties, to demonstrate that the steam dryer will maintain its structural integrity over its design life considering variations in plant parameters (such as reactor pressure and core flow rate).

(d) Specify periodic steam dryer inspections during refueling outages.

A periodic steam dryer inspection program will be implemented with the following key elements:

1. During the first two scheduled refueling outages after reaching full power conditions, a visual inspection will be conducted of all accessible areas and susceptible locations of the steam dryer in accordance with accepted industry guidance on steam dryer inspections. The results of these baseline inspections will be provided to the NRC within 60 days following startup after each outage.
2. At the end of the second refueling outage following full power operation, an updated SDMP reflecting a long-term inspection plan based on plant-specific and industry operating experience will be provided to the NRC within 180 days following startup from the second refueling outage.

11.0 CONCLUSIONS

This report describes the GEH ESBWR steam dryer analysis methodology that will be used to evaluate the structural response to FIV loads under normal operating conditions, as well the ASME load combinations that demonstrate that the ESBWR steam dryer will maintain structural integrity during normal, transient, and accident conditions. The analyses must show that the dryer will maintain its structural integrity (and not generate loose parts) during plant operation, including considerations for fatigue due to acoustic and hydrodynamic fluctuating pressure loads. This report also provides the overall dryer analysis framework, which includes the PBLE01 load definition method (Reference 11), the ESBWR design load definition (Reference 6), the structural analyses including the application of bias, uncertainty, and design margin, and the power ascension test program.

The structural analysis follows a staged or phased approach, which leverages information that will be made available as the design process progresses (especially through the power ascension test program). The culmination of the analysis and test program will be a validated design, supported by a benchmark as a basis for bias and uncertainty, which will closely follow the example implementation provided in NEDE-33408P. The PBLE01 and structural analysis approach have been applied to a replacement steam dryer under power uprate conditions as an example of a successful implementation of the GEH methodology to allow a COL applicant to incorporate by reference this information in its FSAR to satisfy RG 1.20.

The structural analysis approach, design criteria, and integrated power ascension test program provide adequate assurance that the ESBWR steam dryer will maintain its structural integrity and not generate loose parts under normal, transient, and accident conditions.

12.0 REFERENCES

[1] U.S. Nuclear Regulatory Commission, Regulatory Guide 1.20 "Comprehensive Vibration Assessment Program for Reactor Internals During Preoperational and Initial Startup Testing," Revision 3, March 2007.

[2] GE Hitachi Nuclear Energy, 26A6642AD, "ESBWR Design Control Document," Tier 2, Chapter 1 – Introduction and General Description of Plant, Sections 1.1 – 1.11.

[3] GE Hitachi Nuclear Energy, 26A6642AP, "ESBWR Design Control Document," Tier 2, Chapter 4 – Reactor.

[4] GE Hitachi Nuclear Energy, "ESBWR Initial Core Transient Analysis," NEDO-33337, Revision 1, Class I (Non-proprietary), April 2009.

[5] GE Hitachi Nuclear Energy, "ESBWR Feedwater Temperature Operating Domain Transient and Accident Analysis," NEDO-33338, Revision 1, Class I (Non-proprietary), May 2009.

[6] GE Hitachi Nuclear Energy, "ESBWR Steam Dryer Acoustic Load Definition," NEDE-33312P, Revision 5, Class III (Proprietary), December 2013 and NEDO-33312, Revision 5, Class I (Non-proprietary), December 2013.

[7] American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section II Part D, 2001 Edition, 2003 Addenda.

[8] GE Hitachi Nuclear Energy, 26A6642AK, "ESBWR Design Control Document," Tier 2, Chapter 3, Sections 3.9 - 3.11.

[9] American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, 2001 Edition, 2003 Addenda.

[10] GE Hitachi Nuclear Energy, 26A6642AN, "ESBWR Design Control Document," Tier 2, Chapter 3, Appendices 3G - 3L.

[11] GE Hitachi Nuclear Energy, "ESBWR Steam Dryer – Plant Based Load Evaluation Methodology – PBLE01 Model Description," NEDE-33408P, Revision 5, Class III (Proprietary), December 2013, and NEDO-33408, Revision 5, Class I (Non-proprietary), December 2013.

[12] Letter, Entergy to USNRC, "Vermont Yankee Nuclear Power Station Report on the Results of Steam Dryer Monitoring," BVY 06-056 (Docket No. 50-271, TAC No. MC0761), June 30, 2006.

[13] GE Hitachi Nuclear Energy, 0000-0101-0766-P-R0, "Main Steam Line Limit Curve Adjustment During Power Ascension," Class III, April 2009.

APPENDIX A
ITAAC FOR REACTOR PRESSURE VESSEL INTERNALS

ESBWR DCD Tier 1, Table 2.1.1-3, "ITAAC for Reactor Pressure Vessel and Internals," specifies in ITAAC 8.b that the steam dryer will meet the requirements of ASME Boiler & Pressure Vessel Code, Subsection NG-3000 (except for weld quality and fatigue factors for secondary structural non-load bearing welds). The discussion below explains how ITAAC acceptance criteria are demonstrated to be met.

Extracted from ESBWR DCD Tier 1, Table 2.1.1-3:

Design Commitment	Inspections, Tests, Analyses	Acceptance Criteria
8b. The RPV internal structures listed in Table 2.1.1-1 (chimney and partitions, chimney head and steam separators assembly, and steam dryer assembly) meet the requirements of ASME B&PV Code, Subsection NG-3000, except for the weld quality and fatigue factors for secondary structural non-load bearing welds.	Inspections will be conducted of the as-built internal structures as documented in the ASME Code design reports.	The RPV internal structures listed in Table 2.1.1-1 1 (chimney and partitions, chimney head and steam separators assembly, and steam dryer assembly) meet the requirements of ASME B&PV Code, Subsection NG-3000, except for the weld quality and fatigue factors for secondary structural non-load bearing welds.

For ITAAC 8b, an ASME Code design report will include sufficient detail to show that the applicable stress limitations are satisfied in ASME BPV Code Section III Article NG-3000, as applicable to the steam dryer, when the component is subject to the loading conditions specified in the Design Specification.

According to ITAAC 8b, the COL Licensee will conduct an inspection of the fabricated, as-built steam dryer prior to its installation into the reactor pressure vessel (RPV). The inspection will include a comparison of the as-built steam dryer to the ASME Code design report, as well as supporting documentation for the design report, which will include documents such as the structural evaluation, construction drawings, deviations, repairs, procurement documentation with receipt inspection records, fabrication records. Prior to installation into the RPV, the COL Licensee will ensure that the NRC has conducted inspection of the steam dryer's numerous documents. NRC inspection activities associated with ITAAC will be described in NRC Inspection Reports. NEI 08-01 includes guidance regarding treatment in the ITAAC closure process of ITAAC-related findings that may be identified.

Once the steam dryer is installed in the RPV, final installation documentation would be added to the scope of documents in the ITAAC closure package of supporting information that demonstrate acceptance criteria are met. The NRC would have an opportunity to review the documents throughout the process and following installation. If any ITAAC findings are identified, those would be dispositioned prior to the COL Licensee issuing an ITAAC closure notification letter. Once ITAAC-related activities are completed, the COL Licensee would process a closure notification letter to the NRC in accordance with NRC-endorsed guidance and the ITAAC Closure Plan.

ITAAC Item 8b in DCD Tier 1 Table 2.1.1-3 requires that an inspection be conducted of the as-built internal structures as documented in an ASME BPV Code Section III design report (see ASME BPV Code Section III, Subsection NCA, Division 1, Subsection NG, and Appendices - 2001 Edition with addenda to and including 2003). For the steam dryer, the design commitment associated with this ITAAC is that the steam dryer assembly meets the requirements of the ASME B&PV Code Section III, Article NG-3000, except for the weld quality and fatigue factors for secondary structural non-load bearing welds. The origin of this requirement is DCD Tier 2 Subsection 3.9.5.4. This design commitment stated in the ITAAC is consistent with NRC guidance in NUREG-0800 Section 3.9.5, "SRP Acceptance Criteria," ¶ 3.

This requirement was implemented in DCD Tier 2 in response to NRC RAI 3.9-252:

> *(Ref. ESBWR DCD Section 3.9.5.4, Rev. 5) The final paragraph of DCD Section 3.9.5.4 requires additional explanation. The design requirements presented for equipment classified as non-safety related class internals are not consistent with requirements presented in other design basis related documents, e.g., Topical Report NEDE-33313P for the steam dryer. Additional discussion should be included in DCD Section 3.9.5.4 to clarify the following:*
>
> *(a) Which non-safety related internals components use selected ASME Code requirements as their design basis.*
>
> *(b) What are the specific ASME Code requirements adopted as the design basis for those components identified in (a) above.*
>
> *(c) For those non-safety related internals components which do not use ASME Code requirements for their design, identify the "accepted industry or engineering practices" which are used for their design.*

GEH response for RAI 3.9-252:

> The nonsafety-related reactor internal components are identified in DCD Tier 2, Section 3.9.5. These components are the chimney and partitions, chimney head and steam separator assembly, steam dryer assembly, feedwater spargers, RPV vent assembly, and surveillance sample holders. None of these components are ASME Code components, but the designs will comply with the requirements of ASME Code Subsection NG-3000 except for the weld quality and fatigue factors for secondary structural non-load bearing welds. Primary structural load bearing welds use quality and fatigue factors as given NG-3000.
>
> The steam dryer assembly uses weld quality and fatigue factors as discussed in Subsections 4.1 and 7.1 of NEDE-33313P.

The response addressed weld requirements for non-safety related reactor internals and is reflected in the ITAAC 8b design commitment scope. NEDE-33313P discusses the weld quality factors and weld fatigue factors for secondary structural non-load bearing welds. As shown, both the DCD and NEDE-33313P apply to the steam dryer.

To clarify, the [[
]]. ASME BPV Code Section III paragraph NG-1122 "Internal Structures" states "...the construction of all internal structures is such as to not affect adversely the integrity of the core support structure". [[

]]. The appropriate weld factors are used, depending upon whether a particular member is primary or secondary. The design report would document which weld factors were used for each weld joint.

The design report is to contain calculations and sketches substantiating that the design is in accordance with the Design Specification and Article NG-3000 requirements. This design report will include results of stress analyses and will document detailed design analyses completion.

The overall process for performing the structural evaluation of the ESBWR steam dryer in preparation for the design report is as follows:

- The finite element model (Section 5) is used to predict stresses resulting from specified ASME load combinations (Section 8 and as described in the design specification). The acoustic load definition in the design specification for the ESBWR steam dryer is described in NEDE-33312P and is supported by NEDC-33408P describing the analytical tool and process for predicting fluctuating pressure loads on the steam dryer for use in the structural analysis.
- Describes material properties used in the analyses per ASME BPV Code (Seciton 3).
- States design criteria with additional limits on the material fatigue strength and information on use of Fatigue Strength Reduction Factors (Section 4).
- Describe vibration analysis and predicted component stresses (Section 6).
- Provides fatigue prediction (Section 7).

When ASME load combination analyses are performed, detail design iterations may need to be made to provide margins for demonstrating that the ESBWR steam dryer is structurally acceptable for its end use.

As specified in the ITAAC, the ASME Code design report showing acceptance to Article NG-3000 using weld quality and weld fatigue factors for secondary structural non-load bearing welds as provided herein will be used by the COL licensee in the ITAAC closure process defined in DCD Tier 2 Section 14.3 and information in Tier 1, Section 1, to demonstrate that the acceptance criteria of the ITAAC have been met. The COL Licensee will verify that the as-built steam dryer assembly conforms to the ASME Code design report.

APPENDIX B
ITAAC FOR MAIN STEAM LINE AND SRV/SAFETY VALVE BRANCH PIPING ACOUSTIC RESONANCE

ESBWR DCD Tier 1, Table 2.1.2-3, "ITAAC for the Nuclear Boiler System," specifies in ITAAC 36 that the main steam line (MSL) and safety relief valve (SRV) and relief valve (RV) branch piping geometry precludes first and second shear layer wave acoustic resonance conditions from occurring and avoids pressure loads on the steam dryer at plant normal operating conditions. The discussion below explains how ITAAC acceptance criteria are demonstrated to be met.

Extracted from ESBWR DCD Tier 1, Table 2.1.1-3:

Design Commitment	Inspections, Tests, Analyses	Acceptance Criteria
36. The main steam line and SRV/SV branch piping geometry precludes first and second shear layer wave acoustic resonance conditions from occurring and avoids pressure loads on the steam dryer at plant normal operating conditions.	Analysis of the as-built piping system and equipment analysis, for acoustic resonance at plant normal operating conditions, will be performed.	The main steam line and SRV/SV branch piping geometry precludes first and second shear layer wave acoustic resonance conditions from occurring and results in no significant pressure loads on the steam dryer at plant normal operating conditions.

The COL Licensee will include documented evidence of an analysis in the ITAAC closure package. This ITAAC depends upon completion of piping design (addressed in Tier 1, Section 3.1), to ensure that the as-built piping and the piping branch-connected safety-relief and safety valves (SRV/SV) are designed to preclude first and second shear layer wave acoustic resonance conditions from occurring. Satisfying this design criterion avoids significant acoustic pressure loads on the steam dryer. The acceptance criteria for the piping and valves as-built dimensions will be contained in an acoustic resonance calculation that provides documented evidence that first and second shear layer wave resonances will not occur with final design dimensions. It is expected that NRC inspectors will conduct inspections of the supporting information and documents as deemed necessary throughout the process. Once the main steam piping is installed, final documentation would be added to the list of documents in the ITAAC closure package of supporting information that demonstrate acceptance criteria are met. The COL Licensee would process a closure notification letter to the NRC in accordance with NRC-endorsed guidance and the ITAAC Management Plan.

ITAAC 36 will be completed in conjunction with completing ITAAC Table 2.1.2-3, Item 2b, with an analysis to verify that the as-built piping and connected SRV/SV dimensions preclude these resonance frequencies. For the low frequency loads, the ESBWR design does not include dead legs in the main steam piping system.

The ESBWR DCD, Section 3L.4.1, and NEDE-33312P, Section 4.1, address the main steam system design to preclude acoustic resonance. The referenced ITAAC Table 2.1.2-3, Item 36, was developed to address piping design features that will be factored into the ESBWR piping design to preclude acoustic resonance frequencies and avoid pressure loads on the steam dryer. These design features are based on lessons learned from industry experience. ITAAC Item 36 was initially added in response to NRC RAI 3.9-134 Supplement 02 (MFN 09-363, June 8, 2009). It was later discussed in the 2009 NRC reactor internals audit and modified in response to NRC reactor internals audit comment 4 (see MFN 09-621, October 8, 2009) to specifically address the first and second shear layer wave. See the GEH responses:

NRC RAI 3.9-134 S02

The GEH response includes a discussion of their general design approach, stating that the main steam lines and branch connection piping for the safety relief valves will be designed to avoid the possibility of any acoustic resonance. However, GEH has not yet submitted the actual design parameters. GEH is requested to submit the actual design parameters of the main steam piping and SRV branch piping, or provide additional detail (design requirements, criteria, methods) to provide assurance that the possibility of acoustic resonance will be avoided and provide associated ITAAC in order to verify this design commitment.

GEH Response

The GEH response includes a discussion of their general design approach, stating that the main steam lines and branch connection piping for the safety relief valves will be designed to avoid the possibility of any acoustic resonance. However, GEH has not yet submitted the actual design parameters. GEH is requested to submit the actual design parameters of the main steam piping and SRV branch piping, or provide additional detail (design requirements, criteria, methods) to provide assurance that the possibility of acoustic resonance will be avoided and provide associated ITAAC in order to verify this design commitment.

GEH has performed preliminary acoustic resonance calculations for the MS, SRV and SV piping based on preliminary design information. These calculations show that the calculated Strouhal numbers are outside the range for which adverse impacts due to acoustic resonances would occur. The calculations were performed at 100% and 102% power.

NRC Comment 4

The staff is concerned about the structural integrity of [[

]].

GEH Response

To clarify that the ITAAC number 36 of Table 2.1.2-3 in Tier 1 applies to both the main steam piping components and the steam dryer, this ITAAC has been revised as shown in the attachment. The revised ITAAC also specifies that it is the first and second shear layer wave acoustic resonance of the main steam line and the SRV/SV standpipe that is specifically avoided. A corresponding change to Tier 2 section 3L.4.1 is also made as shown in the attachment to support the Tier 1 change. [[

]].

In both of the above responses, changes were made to the ESBWR DCD. In the March 2012 NRC audit, the preliminary acoustic resonance calculations mentioned in the responses quoted above were reviewed. These preliminary calculations, using preliminary piping design assumptions, indicate that [[

]]

The preliminary calculations also compare the [[

]] The ESBWR main steam system has two longer and two shorter main steam lines with 5 and 4 SRV/SVs mounted perpendicular to the main steam pipe centerline. [[

]] Also, consistent with the response to NRC Audit Comment 4 (above), [[

]]

The subject piping is ASME Code Class 1 piping in the main steam lines between the reactor pressure vessel and the second isolation valve outside containment. Thus, the piping is subject to preoperational and initial startup vibration testing in accordance with ASME OM S/G-2003.

The ITAAC specifies that an analysis of the as-built piping system and equipment analysis, for acoustic resonance at plant normal operating condition, will be performed. Accordingly, the COL Licensee will perform an analysis comparing the main steam line and SRV/SV branch piping final design geometry to the as-built installed piping and equipment to ensure that the design features are appropriately incorporated into the as-built piping.

Specific to the acceptance criteria, preclusion of first and second shear layer wave acoustic resonance in the main steam piping final design will be addressed during the detailed design phase through acoustic analysis calculations. The piping acoustic analysis is used in conjunction with the piping design ITAAC for optimizing results (see ITAAC Table 2.1.2-3, Item 2b).

A design report will be prepared in accordance with ESBWR DCD Tier 1 Section 1.1.2.2 "Implementation of ITAAC" to satisfy the Acceptance Criterion for the standard plant design. The COL licensee will reference the design report in a COL submittal to satisfy Acceptance Criteria for ITAAC 36 of ESBWR DCD Tier 1 Table 2.1.2-3. This is in accordance with the process defined in Tier 2, Section 14.3.3.1, "Design of Piping Systems and Components," of the ESBWR DCD. Thus, the standard ITAAC closure process is applicable to ITAAC 36 and does not require special treatment by the COL applicant. Verification that resonance frequency does not impact the steam dryer will be documented in the ASME Code design report and through startup testing.

The high-amplitude low-frequency loads that have been unique to Susquehanna Steam Electric Station (SSES) are attributable to dead leg branches installed on the A and D main steam piping runs. The dead leg branches are acting as resonating chambers that amplify the steam piping acoustics at the frequency where a quarter-wavelength achieves resonance in the dead leg. Other than this frequency peak on the A and D steam piping runs, the acoustic amplitude profiles of all four SSES main steam piping runs are comparable.

The occurrence of high-amplitude low-frequency acoustic loads due to the amplification provided by branch piping dead legs, such as experienced at SSES, is precluded in the ESBWR main steam piping design because the ESBWR design does not have these dead legs. Therefore, an ESBWR will not experience the particular acoustic loads that are observed at SSES.

As described in Tier 2, Section 3L.4.6, "Instrumentation and Startup Testing," of the ESBWR DCD, the main steam lines for the prototype plant will be instrumented to measure the acoustic pressures in the steam lines during startup through normal plant operating conditions. These measurements will confirm that the ESBWR main steam line design precludes SRV and SV branch line acoustic resonances, as well as the high amplitude low frequency acoustic loads observed at SSES.