Enclosure 5

MFN 13-007

GE Hitachi Nuclear Energy, "ESBWR Steam Dryer Structural Evaluation," NEDO-33313, Class I (Non-Proprietary) Revision 3, February 2013

Public Version

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GE Hitachi Nuclear Energy

NEDO-33313
Revision 3
DRF Section 0000-0076-2527 R9
February 2013

Non-Proprietary Information-Class I (Public)

Engineering Report

ESBWR STEAM DRYER STRUCTURAL EVALUATION

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SUMMARY OF CHANGES

Location	Comment
All	Revised document to Revision 3. Deleted "-A" to denote that the current version has not been reviewed by the NRC.
Cover Page	Copyright date updated
S1.0, 1st para, 3rd sentence	Updated "Revision 2" to "Revision 3."
S1.0	Added overview of dryer structural evaluation process.
S4.0	Revised in response to MFN 12-086, Revision 2, dated February 11, 2013.
S4.1, 1st para, last sentence	Revised to reflect MASR = 2.0 per MFN 12-130, dated December 12, 2012.
S4.1, 2nd para, first sentence	Deleted steam line pressure measurements consistent with deletion of PBLE "Method 2" per MFN 12-130, dated December 12, 2012.
S4.1, 2nd para, last two sentences	Changed "peak stress" to "highest stress" (two places) per MFN 12-077, Revision 2, dated February 15, 2013.
S4.1, 3rd para, first sentence	Revised to use on-dryer instrumentation for subsequent plants per MFN 12-130, dated December 12, 2012.
S4.1, 3rd para, last sentence	Changed "peak stress" to "highest stress" per MFN 12-077, Revision 2, dated February 15, 2013.
S4.1, 7th para	Revised method of obtaining [[ ]] per MFN 12-077, Revision 2, dated February 15, 2013.
S4.1, 8th para, first tick mark	Revised method of obtaining [[ ]] per MFN 12-077, Revision 2, dated February 15, 2013.
S4.1, 9th para	Changed "peak stress" to "highest stress" (two places) per MFN 12-077, Revision 2, dated February 15, 2013.
S4.1, 10th para	Revised method of obtaining [[ ]] per MFN 12-077, Revision 2, dated February 15, 2013.
S4.1, 11th para, first sentence	Changed "peak stress" to "highest stress" per MFN 12-077, Revision 2, dated February 15, 2013.
S4.1, 13th para, second sentence	Changed "peak stress" to "highest stress" per MFN 12-077, Revision 2, dated February 15, 2013.

Location	Comment
S4.2, 3rd para	Revised in response to MFN 12-086, Revision 2, dated February 11, 2013.
S5.1, 1st para	Added shell-to-solid element interface modeling per MFN 12-055, Revision 2, dated February 14, 2013.
S5.1, 6th para, item (1)	Changed "peak stress" to "highest stress" per MFN 12-077, Revision 2, dated February 15, 2013.
S5.2.2	Revised to be consistent with the end-to-end benchmark documented in NEDC-33408 Rev. 2.
S5.2.2, [[ ]]	Changed "peak stress" to "highest stress" per MFN 12-077, Revision 2, dated February 15, 2013.
S5.2.3	Deleted references to PBLE benchmarking in NEDC-33408 Supplement 1.
S5.2.4, 3rd para, item 1	Revised to use on-dryer instrumentation for subsequent plants per MFN 12-130 dated December 12, 2012.
S5.2.4, 3rd para, items 1 and 2	Deleted steam line pressure measurements consistent with deletion of PBLE "Method 2" per MFN 12-130, dated December 12, 2012.
S5.2.4	Changed "peak stress" to "highest stress" (21 places) per MFN 12-077, Revision 2, dated February 15, 2013.
S5.2.4	Changed "peak stress" to "highest stresses" (two places) per MFN 12-077, Revision 2, dated February 15, 2013.
S5.2.5	Revised to be consistent with the end-to-end benchmark documented in NEDC-33408 Rev. 2.
S8.3	Corrected section reference.
S9.1, 2nd para, 1st bullet	Changed "peaked stressed components" to "highest stressed components" per MFN 12-077, Revision 2, dated February 15, 2013.
S9.1, 2nd para, 2nd bullet	Changed "peak stress location" to "highest stress location" per MFN 12-077, Revision 2, dated February 15, 2013.
S9.1, 2nd para, 3rd bullet	Changed "peak stress response time" to "highest stress response time" per MFN 12-077, Revision 2, dated February 15, 2013.
S9.1	Deleted steam line pressure measurements consistent with deletion of PBLE "Method 2" per MFN 12-130, dated December 12, 2012.
S9.1	Revised to use on-dryer instrumentation for subsequent plants per MFN 12-130 dated December 12, 2012.
S9.2	Changed "peak stress" to "highest stress" (nine places) per MFN 12-077, Revision 2, dated February 15, 2013.

Location	Comment
S9.2, 6th para, Item (2)	Changed "peak alternating stress" to "highest alternating stress" per MFN 12-077, Revision 2, dated February 15, 2013.
S9.2	Deleted obsolete reference for fatigue endurance limit.
S9.2	Revised outer hood acceptance criteria to be consistent with a design MASR = 2.0 per MFN 12-130, dated December 12, 2012.
S9.2	Revised to use on-dryer instrumentation for subsequent plants per MFN 12-130 dated December 12, 2012.
S11.0	Updated References 1 and 9 to be consistent with revisions to these reports.
S11.0	Deleted Reference 7 consistent with deletion of PBLE "Method 2" per MFN 12-130, dated December 12, 2012.
Attachment 1	Deleted.

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ACRONYMS AND ABBREVIATIONS

Term	Definition
ABWR	Advanced Boiling Water Reactor
ASME	American Society of Mechanical Engineers
ATWS	Anticipated Transiet Without Scram
BWR	Boiling Water Reactor
DP	Differential Pressure
DW	Dead Weight
ESBWR	Economic Simplified Boiling Water Reactor
GEH	GE Hitachi Nuclear Energy
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Model
FIV	Flow Induced Vibration
HF	High Frequency
IOT	Infrequent Operating Transient
LBL	Large Break LOCA
LOCA	Loss-of-Coolant Accident
LF	Low Frequency
MSLB	Main Steam Line Break
PBLE	Plant Based Load Evaluation
PS	Power Spectrum
RMS	Root Mean Square
RPV	Reactor Pressure Vessel
SBL	Small Break LOCA
SCF	Stress Concentration Factor
SOT	System Operating Transient
SRSS	Square Root Sum of the Squares
SRV	Safety Relief Valve
SSE	Safe Shutdown Earthquake
SSES	Susquehanna Steam Electric Station
TSV	Turbine Stop Valve
VY	Vermont Yankee

1.0 INTRODUCTION

This engineering report will document the finite element (FE) stress analyses of the Economic Simplified Boiling Water Reactor (ESBWR) steam dryer. 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, Revision 3 of this report only includes a description of the analysis approach and design criteria. A detailed finite element model (FEM) is used to perform the structural dynamic analyses in order to predict the steam dryer's susceptibility to fatigue under flow induced vibration (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.

The load definition for the ESBWR steam dryer is described in NEDE-33312P, Reference 1. When the fatigue analysis and ASME load combination analysis described is performed, the necessary design iterations will be made to include the resultant stresses and fatigue margins demonstrating the ESBWR steam dryer is structurally acceptable for end use.

The approach used for the ESBWR steam dryer structural evaluation includes the following:

- [[

]]

2.0 STEAM DRYER 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.

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 2.

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 3, as defined in Reference 4, 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 5. [[

]]

A [[

]]

The stress may also be obtained from the [[

]]

If the [[

]]

The specified SCF [[

]]

4.2 Weld Quality Factor

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

]]

4.3 ASME Code Stress Limits for Load Combinations

The ASME Code stress limits from Subsection NG of Reference 4 are listed in Table 4.1.

Table 4.1 ASME Code Stress Limits [Reference 4]

Service Level	Stress Category	Core Support Structures Stress limits (NG)
Service Levels A&B	P_m	S_m
	$P_m + P_b$	$1.5S_m$
Service Levels C	P_m	$1.5S_m$
	$P_m + P_b$	$2.25S_m$
Service level D	P_m	Min(.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
S_m:ASME Code Design Stress Intensity
S_u:Ultimate strength

Note: Service Level Limits for Service Levels A, B and C are according to NG-3221 and Appendix F Paragraph F-1331 for Level D. Upset condition stress limits are increased by 10% above the limits shown in these table per NG-3223(a).

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Figure 4-1. Weld Fatigue Factor Flow Diagram

5.0 STEAM DRYER FEA MODEL AND APPLIED LOADS

5.1 Full Steam dryer Shell Finite Element Model

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5.2 Dynamic Pressure Loads

5.2.1 FIV LOADS

The FIV loading time history and any necessary loading scale factors are taken from Reference 1. [[

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5.2.2 BIAS AND UNCERTAINTY OF THE STEAM DRYER FIV STRESS

Reference 9 describes the end-to-end benchmarking process used to establish the bias and uncertainty values for the steam dryer FIV stress analysis. Appendix F of Reference 9 provides the [[

]]

5.2.3 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. [[

]]

5.2.4 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, [[

]]

Table 5.1
Time Domain Strain Gage Data Statistics

[[

]]

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 [[

]]

5.2.5 BIAS AND UNCERTAINTY AND BENCHMARKING USING HARMONIC FE FIV SOLUTION

[[

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5.3 ASME Loads

The loads representing normal plant operation and other operating events as described in Section 8.0 will be generated for the FEM.

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. [[
]]

7.0 FATIGUE PREDICTION

7.1 Fatigue Calculation

[[

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

7.2 Frequency Content of the Structural Response

In order to understand the structural [[

]]

8.0 ASME LOAD COMBINATIONS

8.1 ASME Load Combinations

Table 8.1 provides the load combinations and describes the load cases to be used in the ASME load combinations stress analysis.

Table 8.1 ASME Load Combinations and Conditions

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

DPf1 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)

8.2 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. [[
]]

8.3 ASME Load Case Stress Results

[[
]] These stresses will then be compared to the criteria from Section 4.3.

9.0 STARTUP TEST

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.

[[

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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 93.8 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)

[[

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10.0 CONCLUSIONS

This report describes how a detailed FEM of the ESBWR steam dryer will be used to predict steam dryer structural responses to FIV loads and ASME load combinations. When the FIV loads from Reference 1 become available, the analysis will be performed as described, and the results will be used to iterate on a steam dryer design that will meet the required fatigue and ASME load combination stress criteria.

11.0 REFERENCES

[1] GE Hitachi Nuclear Energy, "ESBWR Steam Dryer Acoustic Load Definition," NEDE-33312P, Revision 3, February 2013.

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

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

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

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

[6] ANSYS Release 11.0, ANSYS Incorporated, 2008.

[7] Deleted.

[8] Deleted.

[9] GE Hitachi Nuclear Energy, "ESBWR Steam Dryer – Plant Based Load Evaluation Methodology," NEDC-33408P, Revision 2, Class III (Proprietary), February 2013, and NEDO-33408, Revision 2, Class I (Non-proprietary), February 2013.

[10] 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.

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

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Figure 2-1. Typical Steam Dryer Installed in RPV

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Figure 5-1. Typical Finite Element Model

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Note: Different Colors represent Different Components

Figure 5-2. Typical Vane Bank End Plates and Divider Plates

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Note: Different Colors represent Different Components

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

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Figure 5-4. Typical Boundary Conditions on Structure

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Figure 7-1. Typical Waterfall Plot (top) and PSD (bottom)