Enclosure 9

MFN 13-091

ESBWR Design Control Document Marked-Up Pages

Public Information

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Changes to ESBWR DCD due to Audit of the
ESBWR Steam Dryer Design Methodology

Changes For:

Tier 1, Chapter 2, “Design Descriptions and ITAAC”

Section 2.1, “Nuclear Steam Supply”

Section 2.1.1, “Reactor Pressure Vessel and Internals”

2. DESIGN DESCRIPTIONS AND ITAAC

This section provides the certified design material for each of the ESBWR systems that is either fully or partially within the scope of the Certified Design.

2.1 NUCLEAR STEAM SUPPLY

The following subsections describe the major Nuclear Steam Supply Systems (NSSS) components of the Reactor Pressure Vessel (RPV) and the Nuclear Boiler System. This section also describes the natural circulation process for the ESBWR.

2.1.1 Reactor Pressure Vessel and Internals

Design Description

The RPV and Internals generate heat and boil water to steam in a direct cycle. The functional arrangement of the RPV and Internals includes the reactor core and reactor internals (see Figure 2.1.1-1). The chimney provides an additional elevation head (or driving head) necessary to sustain natural circulation flow through the RPV. The chimney also forms an annulus separating the subcooled recirculation flow returning downward from the steam separators and feedwater from the upward steam-water mixture flow exiting the core. The steam is separated from the steam-water mixture by passing the mixture sequentially through an array of steam separators attached to a removable cover on the top of the chimney assembly, and through the steam dryer, resulting in outlet dry steam. The water mixes with the feedwater as it comes into the RPV through the feedwater nozzle. RPV internals consist of core support structures and other equipment.

The RPV is located in the containment. Internal component locations are shown on Figure 2.1.1-1.

The reactor core contains a matrix of fuel rods assembled into fuel assemblies using structural elements. Control rods in the reactor perform the functions of power distribution shaping, reactivity control, and scram reactivity insertion for safety shutdown response. The core is designed for 1132 fuel bundles and 269 control rods arranged as shown in Figure 2.1.1-2.

(1) The functional arrangement of the RPV and Internals is as described in the Design Description of this Subsection 2.1.1, Table 2.1.1-1 and Figure 2.1.1-1.

(2) The key dimensions (and acceptable variations) of the as-built RPV are as described in Table 2.1.1-2.

(3) a1. The RPV and its components identified in Table 2.1.1-1 (shroud, shroud support, top guide, core plate, control rod guide tubes and fuel supports) as ASME Code Section III are designed in accordance with ASME Code Section III requirements.

a2. The RPV and its components identified in Table 2.1.1-1 (shroud, shroud support, top guide, core plate, control rod guide tubes and fuel supports) as ASME Code Section III shall be reconciled with the design requirements.

a3. The RPV and its components identified in Table 2.1.1-1 (shroud, shroud support, top guide, core plate, control rod guide tubes and fuel supports) as ASME Code Section III are fabricated, installed, and inspected in accordance with ASME Code Section III requirements.

(4) Pressure boundary welds in the RPV meet ASME Code Section III non-destructive examination requirements.

(5) The RPV retains its pressure boundary integrity at its design pressure.

(6) The equipment identified in Table 2.1.1-1 as Seismic Category I can withstand Seismic Category I loads without loss of safety function.

(7) RPV surveillance specimens are provided from the forging material of the beltline region and the weld and heat affected zone of a weld typical of those adjacent to the beltline region. Brackets welded to the vessel cladding at the location of the calculated peak fluence are provided to hold the removable specimen holders and a neutron dosimeter in place.

(8) a. The RPV internal structures listed in Table 2.1.1-1 (chimney and partitions, chimney head and steam separators assembly, and steam dryer assembly) must meet the limited provisions of ASME Code Section III regarding certification that these components maintain structural integrity so as not to adversely affect RPV core support structure.

b. 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.

(9) The initial fuel to be loaded into the core will withstand flow-induced vibration and maintain fuel cladding integrity during operation.

(10) The fuel bundles and control rods intended for initial core load have been fabricated in accordance with the approved fuel and control rod design.

(11) The reactor internals arrangement conforms to the fuel bundle, instrumentation, neutron sources, and control rod locations shown on Figure 2.1.1-2.

(12) The number and locations of pressure sensors installed on the steam dryer for startup testing ensure accurate pressure predictions at critical locations.

(13) The number and locations of strain gages and accelerometers installed on the steam dryer for startup testing are capable of monitoring the most highly stressed components, considering accessibility and avoiding discontinuities in the components.

(14) The number and locations of accelerometers installed on the steam dryer for startup testing are capable of identifying potential rocking and of measuring the accelerations resulting from support and vessel movements.

(15) The initial fuel to be loaded into the core will be able to withstand fuel lift and seismic and dynamic loads under normal operation and design basis conditions.

~~(15)~~(16) The as-built steam dryer predicted peak stress is below the fatigue limitation.

Table 2.1.1-3

ITAAC For The Reactor Pressure Vessel and Internals

Design Commitment	Inspections, Tests, Analyses	Acceptance Criteria
15. The initial fuel to be loaded into the core will be able to withstand fuel lift and seismic and dynamic loads under normal operation and design basis conditions.	An analysis of the fuel lift and seismic and dynamic loads will be performed on the fuel bundle design that will be loaded into the ESBWR initial core.	The initial fuel to be loaded into the core will have primary stresses and maximum fuel bundle lift out of the fuel support piece that do not exceed the allowable values provided in the approved Fuel Assembly Mechanical Design Report.
16. The as-built steam dryer predicted peak stress is below the fatigue limitation.	Analyses using NRC-approved methodologies are performed.	A report of the fatigue analyses of the as-built steam dryer ~~verify~~ exists and demonstrates that the maximum calculated alternating stress intensity ~~meets or exceeds~~ provides at least a Minimum Alternating Stress Ratio of 2.0 to the allowable alternating stress intensity of 93.7 MPa (13,600 psi).

Changes to ESBWR DCD due to Audit of the
ESBWR Steam Dryer Design Methodology

Changes For:

Tier 2, Chapter 1, Table 1.6-1, “Referenced GE/GEH Reports”

and

Tier 2, Chapter 1, Table 1.9-21, “NRC Regulatory Guides Applicability to ESBWR”

and

Tier 2, Appendix 1D, Table 1D-1, “Summary of Tier 2* Information”

Table 1.6-1

Referenced GE / GEH Reports

Report No.	Title	Section No.
NEDO-33306	GE Hitachi Nuclear Energy, "ESBWR Severe Accident Mitigation Design Alternatives," NEDO-33306, Class I (Non-proprietary), Revision 4, October 2010.	19.2
NEDE-33312P NEDO-33312	*[GE Hitachi Nuclear Energy, "ESBWR Steam Dryer Acoustic Load Definition," NEDE-33312P, Class III (Proprietary), Revision ~~3~~5, ~~February~~ December 201~~0~~3, and NEDO-33312, Class I (Non-proprietary), Revision ~~3~~5, ~~February~~December 201~~0~~3.*]*	3L
NEDE-33313P NEDO-33313	*[GE Hitachi Nuclear Energy, "ESBWR Steam Dryer Structural Evaluation," NEDE-33313P, Class III (Proprietary), Revision ~~3~~5, ~~February~~ December 2013~~0~~, and NEDO-33313, Class I (Non-proprietary), Revision ~~3~~5, ~~February~~ December 201~~0~~3.*]*	3.9, 3L
NEDC-33326P-A NEDO-33326-A	*[Global Nuclear Fuel, "GE14E for ESBWR Initial Core Nuclear Design Report," NEDC-33326P-A, Revision 1, Class III (Proprietary), and NEDO-33326-A, Revision 1, Class I (Non-proprietary), September 2010.*]*	4.3, 4.4, 4A, 4D, 15.0, 15.2, 15.3, 15.5
NEDO-33337	GE Hitachi Nuclear Energy, "ESBWR Initial Core Transient Analyses," NEDO-33337, Class I (Non-proprietary), Revision 1, April 2009.	4.4, 4D, 15.0, 15.2, 15.3, 15.5, 15D
NEDO-33338	GE Hitachi Nuclear Energy, "ESBWR Feedwater Temperature Operating Domain Transient and Accident Analysis," NEDO-33338, Class I (Non-proprietary), Revision 1, May 2009.	1.1, 4.4, 4D, 6.2, 6.3, 15.0, 15.2, 15.3, 15.5, 15D Chapter 16, Sect. 5.6.3
NEDO-33373-A	GE-Hitachi Nuclear Energy, "Dynamic, Load-Drop, and Thermal-Hydraulic Analyses for ESBWR Fuel Racks," NEDO-33373-A, Revision 5, Class I (Non-proprietary), October 2010.	9.1

Table 1.6-1

Referenced GE / GEH Reports

Report No.	Title	Section No.
NEDC-33374P-A NEDO-33374-A	[*GE-Hitachi Nuclear Energy, "Safety Analysis Report for Fuel Storage Racks Criticality Analysis for ESBWR Plants," NEDC-33374P-A, Revision 4, Class III (Proprietary) September 2010, and NEDO-33374-A, Revision 4, Class I (Non-proprietary), September 2010.*]*	9.1
NEDE-33391	GE Hitachi Nuclear Energy, "ESBWR Safeguards Assessment Report," NEDE-33391, Revision 3, March 2010 – Safeguards Information.	13.6
NED~~C~~E-33408P NEDO-33408	*[GE Hitachi Nuclear Energy, "ESBWR Steam Dryer – Plant Based Load Evaluation Methodology, PBLE01 Model Description," NED~~C~~E-33408P, Class III (Proprietary), Revision 5, ~~February~~ December 201~~0~~3, and NEDO-33408, Class I (Non-proprietary), Revision 5~~,~~ ~~February~~ December 2013~~0~~.]**	3L
NEDO-33411	GE Hitachi Nuclear Energy, "Risk Significance of Structures, Systems and Components for the Design Phase of the ESBWR," NEDO-33411, Class I (Non-proprietary), Revision 2, February 2010.	17.4
NEDE-33440P NEDO-33440	GE Hitachi Nuclear Energy "ESBWR Safety Analysis – Additional Information," NEDE-33440P, Class III (Proprietary), and NEDO-33440, Class I (Non-proprietary), Revision 2, March 2010.	3.6, 6.2
NEDC-33456P NEDO-33456	*[Global Nuclear Fuel, "Full-Scale Pressure Drop Testing for a Simulated GE14E Fuel Bundle," NEDC-33456P, Class III (Proprietary), and NEDO-33456, Class I (Non-proprietary), Revision 0, March 2009.]**	4.4
NEDE-33516P-A NEDO-33516-A	[*GE Hitachi Nuclear Energy, "ESBWR Qualification Plan Requirements for a 72-Hour Duty Cycle Battery," NEDE-33516P-A, Revision 2, Class III (Proprietary), September 2010, and NEDO-33516-A, Revision 2, Class I (Non-proprietary), September 2010.*]*	3.11

Table 1.9-21

NRC Regulatory Guides Applicability to ESBWR

RG No.	Regulatory Guide Title	Appl. Rev.	Issued Date	ESBWR Appli-cable?	Comments
1.20	Comprehensive Vibration Assessment Program for Reactor Internals During Preoperational and Initial Startup Testing	2 and 3	05/1976 and 03/2007	Yes	Performed During Power Ascension Testing
1.21	Measuring, Evaluating, and Reporting Radioactivity in Solid Wastes and Releases of Radioactive Materials in Liquid and Gaseous Effluents from Light-Water-Cooled Nuclear Power Plants	1	06/1974	Yes	
1.22	Periodic Testing of Protection System Actuation Functions	0	02/1972	Yes	
1.23	Onsite Meteorological Programs	0	02/1972	Yes	BSP. See also proposed Rev 1 published 04/1986 as ES 926-4.
1.24	Assumptions Used for Evaluating the Potential Radiological Consequences of a Pressurized Water Reactor Radioactive Gas Storage Tank Failure	0	03/1972	No	PWR only
1.25	Assumptions Used for Evaluating the Potential Radiological Consequences of a Fuel Handling Accident in the Fuel Handling and Storage Facility for Boiling and Pressurized Water Reactors	0	03/1972	No	Superseded by RG 1.183 for new plants.
1.26	Quality Group Classifications and Standards for Water-, Steam-, and Radioactive-Waste-Containing Components of Nuclear Power Plants	3	02/1976	—	See Table 1.9-21a for URD optimization comment and Table 1.9-21b

Table 1D-1

Summary of Tier 2* Information

Location	Short Description of Tier 2* Information	Expiration
S3.9.3.7.2	Reactor Pressure Vessel Sliding Supports	First Full Power
S3.9.3.9.1	Threaded Fasteners – ASME B&PV Code Class 1, 2 and 3 – Material Selection	First Full Power
S3.9.3.9.2	Threaded Fasteners – ASME B&PV Code Class 1, 2 and 3 – Special Materials Fabrication Processes and Special Controls	First Full Power
S3.9.3.9.3	Threaded Fasteners – ASME B&PV Code Class 1, 2 and 3 – Preservice and Inservice Inspection Requirements	First Full Power
Ref 3.9-7	NEDE-33313P/NEDO-33313, ESBWR Steam Dryer Structural Evaluation	None
Table 3.9-2	Load Combinations and Acceptance Criteria for Safety-Related, ASME B&PV Code Class 1, 2 and 3 Components, Component Supports, and Class CS Structures	First Full Power
Table 3.9-9	Load Combinations and Acceptance Criteria for Class 1 Piping Systems	First Full Power
Table 3.9-10	Snubber Loads	First Full Power
Table 3.9-11	Strut Loads	First Full Power
Table 3.9-12	Linear Type (Anchor and Guide) Main Steam Piping Support	First Full Power
S3.10.1.1	Selection of Qualification Method	First Full Power
Ref 3.11-6	LTR NEDE-33516P, ESBWR Qualification Plan Requirements for a 72-Hour Duty Cycle Battery	First Full Power
S3A.2	RB/FB complex, CB and FWSC shape, dimensions and embedment depths	First Full Power
Table 3A.2-1	Standard ESBWR Building Dimensions	First Full Power
S3A.3.1	Generic Site Conditions	First Full Power
S3A.3.2	North Anna ESP Site Conditions	First Full Power
Table 3A.3-1	Generic Site Properties for SSI Analysis	First Full Power
Table 3A.3-2	North Anna Site-specific Properties for SSI Analysis	First Full Power
Table 3A.3-3	Layered Site Cases	First Full Power
S3A.4.1	Input motion for SSI analysis	First Full Power

Table 1D-1

Summary of Tier 2* Information

Location	Short Description of Tier 2* Information	Expiration
S3A.9, S3A.9.1, S3A.9.2, S3A.9.3	Site Envelope Seismic Responses	First Full Power
Table 3A.9-1a to 3A.9-1h	Enveloping Seismic Loads	First Full Power
Table 3A.9-2a to 3A.9-2e	Enveloping Seismic Loads for LOCA Flooding	First Full Power
Table 3A.9-3a to 3A.9-3i	Enveloping Maximum Vertical Acceleration	First Full Power
Table 3A.9-4a to 3A.9-4e	Enveloping Maximum Vertical Acceleration for LOCA Flooding	First Full Power
Figure 3A.9-1a to 3A.9-3l	Enveloping Floor Response Spectra	First Full Power
Appendix 3B	Containment Hydrodynamic Load Definitions	First Full Power
Table 3D.1-1	Computer Program User Details	First Full Power
Appendix 3F	Response of Structures to Containment Loads	First Full Power
Appendix 3G	Design Details and Evaluation Results of Seismic Category I Structures	First Full Power
Ref 3H.4-8	LTR NEDE-33536P/NEDO-33536, Control Building and Reactor Building Environmental Temperature Analysis for ESBWR	First Full Power
Appendix 3I	Designated NEDE-24326-1-P Material Which May Not Change Without Prior NRC Approval	First Full Power
Ref 3L-5	NEDE-33312P/NEDO-33312, ESBWR Steam Dryer Acoustic Load Definition	None
Ref 3L-6	NEDE-33313P/NEDO-33313, ESBWR Steam Dryer Structural Evaluation	None
Ref 3L-8	NEDE-33408P/NEDO-33408, ESBWR Steam Dryer - Plant Based Load Evaluation Methodology, PBLE01 Model Description	None
Chapter 4		
Ref 4.2-4	LTR NEDE-33240P/NEDO-33240, GE14E Fuel Assembly Mechanical Design Report	None

Changes to ESBWR DCD due to Audit of the

ESBWR Steam Dryer Design Methodology

Changes For:

Tier 2, Chapter 3, “Design of Structures, Components, Equipment, and Systems”

Subsection 3.9.2.3, “Dynamic Response of Reactor Internals Under Operational Flow Transients and Steady-State Conditions”

and

Subsection 3.9.2.4, “Initial Startup Flow Induced Vibration Testing of Reactor Internals”

and

Subsection 3.9.5.3, “Loading Conditions”

and

Subsection 3.9.9, “COL Information”

and

Subsection 3.9.10, “References”

bolts or other suitable fastening strong enough to prevent overturning or sliding. The effect of friction on the ability to resist sliding is neglected. The effect of upward dynamic loads on overturning forces and moments is considered. Unless specified otherwise, anchorage devices are designed in accordance with the requirements of the ASME B&PV Code, Subsection NF, or ANSI/AISC-N690 and ACI 349.

Dynamic design data are provided in the form of acceleration response spectra for each floor area of the equipment. Dynamic data for the ground or building floor to which the equipment is attached are used. For the case of equipment having multiple supports with different dynamic motions, an upper bound envelope of all the individual response spectra for these locations is used to calculate maximum inertial responses of items with multiple supports.

Refer to Subsection 3.9.3.5 for additional information on the dynamic qualification of valves.

Supports

Subsections 3.9.3.7 and 3.9.3.8 address analyses or tests that are performed for component supports to assure their structural capability to withstand seismic and other dynamic excitations.

3.9.2.3 Dynamic Response of Reactor Internals Under Operational Flow Transients and Steady-State Conditions

[*The major reactor internal components within the vessel are subjected to extensive testing, coupled with dynamic system analyses, to properly evaluate the resulting FIV phenomena during normal reactor operation and from anticipated operational transients.*

In general, the vibration forcing functions for operational flow transients and steady-state conditions are not predetermined by detailed analysis. The vibration forcing functions for operational flow transients and steady state conditions are determined by first postulating the source of the forcing function, such as forces due to flow turbulence, symmetric and asymmetric vortex shedding, pressure waves from steady state and transient operations. Based on these postulates, prior startup and other test data from similar or identical components are examined for the evidence of the existence of such forcing functions. Special analysis of the response signals measured for reactor internals of many similar designs is performed to obtain the parameters, which determine the amplitude and modal contributions in the vibration responses. Based on these examinations, the magnitudes of the forcing functions and response amplitudes are derived. These magnitudes are then used to calculate the expected ESBWR responses for each component of interest during steady state and transient conditions. This study provides useful predictive information for extrapolating the results from tests of components with similar designs. This vibration prediction method is appropriate where standard hydrodynamic theory cannot be applied due to complexity of the structure and flow conditions. Elements of the vibration prediction method are outlined as follows:

- *Dynamic modal analysis of major components and subassemblies is performed to identify vibration modes and frequencies. The analysis models used for Seismic Category I structures are similar to those outlined in Subsection 3.7.2.*
- *Data from previous plant vibration measurements are assembled and examined to identify predominant vibration response modes of major components. In general, response modes are similar but response amplitudes vary among Boiling Water Reactors (BWRs) of differing size and design.*

- *Parameters are identified which are expected to influence vibration response amplitudes among the several reference plants. These include hydraulic parameters such as velocity and steam flow rates and structural parameters such as natural frequency and significant dimensions.*

- *Correlation functions of the parameters are developed which, multiplied by response amplitudes, tend to minimize the statistical variability between plants. A correlation function is obtained for each major component and response mode.*

- *Predicted vibration amplitudes for components of the prototype plants are obtained from these correlation functions based on applicable values of the parameters for the prototype plants. The predicted amplitude for each dominant response mode is stated in terms of a range, taking into account the degree of statistical variability in each of the correlations. The predicted mode and frequency are obtained from the dynamic modal analyses.*

The dynamic modal analysis forms the basis for interpretation of the initial startup test results (Subsection 3.9.2.4). Modal stresses are calculated and relationships are obtained between sensor response amplitudes and ~~peak~~highest component stresses for each of the lower normal modes.

Details of the special signal analyses of the vibration sensors are given below:

The test data from sensors (accelerometers, strain gages, and pressure sensors) installed on reactor internal components are first analyzed through signal processing equipment to determine the spectral characteristics of these signals. The spectral peak magnitudes and the frequencies at the spectral peaks are then determined. These spectral peak frequencies are then classified as natural frequencies or forced frequencies. If a spectral peak is classified as being from a natural frequency, its amplitude is then determined using a band-pass filter if deemed necessary. The resultant amplitude is then identified as the modal response at that frequency. This process is used for all frequencies of interest. Thus the modal amplitudes at all frequencies of interest are determined. If a spectral peak is identified as being from a forced frequency, the source (such as the vane passing frequency of a pump) is identified. Again, its magnitude is determined using a band-pass filter if deemed necessary.

The modal amplitudes and the forced response amplitudes are then used to calculate the expected ESBWR amplitudes for the same component. These ESBWR expected amplitudes are determined by calculating the expected changes in the forcing function magnitudes from the test component to the ESBWR component. For example, for flow turbulence excited components, the magnitudes are determined by ratio with the flow velocity squared.

A flow chart of the above process is shown in Figure 3.9-6.

The allowable vibratory amplitude in each mode is that which produces a ~~peak~~highest stress amplitude of ±68.95 MPa (±10,000 psi). For the steam dryer and its components, a higher allowable ~~peak~~highest stress limit is used as explained in the following paragraphs.

Vibratory loads are continuously applied during normal operation and the stresses are limited to ±68.95 MPa (±10,000 psi), with the exception of the steam dryer, in order to prevent fatigue failure. Prediction of vibration amplitudes, mode shapes, and frequencies of normal reactor *operations are based on statistical extrapolation of actual measured results on the same or similar components in reactors now in operation.*

Extensive predictive evaluations have been performed for the steam dryer loading and structural evaluation. These evaluations are described in Appendix 3L.4. In the dryer design and in the development of the initial strain and accelerations acceptance limits used during startup, the fatigue analysis performed for the ESBWR steam dryer uses a fatigue limit stress amplitude of 93.7 MPa (13,600 psi). For additional conservatism in the predictive analysis, the analysis stress results will also meet a minimum alternating stress ratio (MASR) of 2.0 between the analysis results and the fatigue acceptance limit. This is verified for the predictive analysis of each as-built steam dryer through inspections, tests, and analyses acceptance criteria during construction.

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 the acceptance limits for the on-dryer instrument measurements during power ascension. ~~For the outer hood component, which is subjected to higher pressure loading in the region of the main steamlines, the fatigue limit stress amplitude is 74.4 MPa (10,800 psi).~~ Following the startup testing of the first unit, a confirmatory stress analysis will be performed based on the on-dryer instrument measurements following startup testing. ~~or if an acceptance limit is reached during power ascension, t~~The ~~load~~ FIV load definition for this analysis is defined from the recorded on-dryer pressure ~~or dryer pressure and steam line data~~measurements. ~~The load definition bias and uncertainty is benchmarked against the dryer pressure sensor data.~~ A structural assessment is performed to benchmark the FE model strain and acceleration predictions against the measured data. The steam dryer ~~peak highest~~ stresses ~~based on test data,~~ are determined using the on-dryer FIV load definition and adjusted for ~~load, FE model, and instrument~~ end-to-end ~~benchmark~~ bias and uncertainties determined from the FE model benchmark~~, is then calculated and maintained less than 93.7 MPa (13,600 psi)~~. 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. If an acceptance limit is reached during power ascension, the same process will be used to confirm that the steam dryer stresses are below the fatigue limit stress amplitude of 93.7 MPa (13,600 psi) and to redefine the acceptance limits for the on-dryer instrument measurements before continuing with the power ascension.

The subsequent ESBWR steam dryers ~~includes~~ will follow the same process as the prototype ESBWR steam dryer, with the predictive analysis verified through inspections, tests, and analyses acceptance criteria; the FIV monitoring ~~via~~ process using ~~main steam line~~ on-dryer instruments during startup testing; and a confirmatory analysis based on on-dryer measurements at full power following startup testing. The acceptance limits for steam dryers in subsequent plants ~~is~~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 steam dryer stresses remain less than 93.7 MPa (13,600 psi) with a MASR of 1.0 ~~allowable stress. The limit is justified because first steam dryer is heavily instrumented, subsequent plants is also monitored for FIV loads, and the load and response is explicitly evaluated based on test data with consideration of bias and uncertainty~~for the startup testing and confirmatory analysis based on on-dryer measured data. The steam dryer is a nonsafety-related component, performs no safety-related functions, and is only required to maintain its structural integrity (no loose parts generated) for normal, transient and accident conditions.

The dynamic loads caused by FIV of the steam separators have been determined using a full-scale separator test under reactor conditions. During the test, the flow rate through the steam separator was 226,000 kg/hr (499,000 lbm/hr) at 7% quality. This is higher than the ESBWR maximum separator flow of 100,700 kg/hr (222,000 lbm/hr) at rated power. Test results show a maximum FIV stress of less than 49.6 MPa (7200 psi), well below the GEH acceptance criterion of 68.9 MPa (10,000 psi). Thus it can be concluded that separator FIV effects are acceptable. Jet impingement from feedwater flow has no significant effect on the steam separator assembly since the separator outer-most cylindrical structure (also referred to as the separator "skirt") is above the feedwater flow impingement area.]*

* Text sections that are bracketed and italicized with an asterisk following the brackets are designated as Tier 2*. Prior Nuclear Regulatory Commission (NRC) approval is required to change.

3.9.2.4 Initial Startup Flow Induced Vibration Testing of Reactor Internals

A reactor internals vibration measurement and inspection program is conducted only during initial startup testing. This meets the guidelines of RG 1.20 with the exception of those requirements related to preoperational testing which cannot be performed for a natural circulation reactor.

Initial Startup Testing

Vibration measurements are made during reactor startup at conditions up to 100% rated flow and power. Steady state and transient conditions of natural circulation flow operation are evaluated. The primary purpose of this test series is to verify the anticipated effect of single- and two-phase flow on the vibration response of internals. Details of the initial startup vibration test program are described in Subsection 3L.4.6 for the steam dryer and Section 3L.5 for other reactor internals. A brief summary is given below.

Vibration sensor types may include strain gauges, displacement sensors (linear variable transformers), and accelerometers.

Accelerometers are provided with double integration signal conditioning to give a displacement output. Sensor locations are provided in Appendix 3L.

In all plant vibration measurements, only the dynamic component of strain or displacement is recorded. Data are recorded and provision is made for selective on-line analysis to verify the overall quality and level of the data. Interpretation of the data requires identification of the dominant vibration modes of each component by the test engineer using frequency, phase, and amplitude information for the component dynamic analyses. Comparison of measured vibration amplitudes to predicted and allowable amplitudes is then to be made on the basis of the analytically obtained normal mode that best approximates the observed mode.

The visual inspections conducted prior to and remote inspections conducted following startup testing are for damage, excessive wear, or loose parts. At the completion of initial startup testing, remote inspections of major components are performed on a selected basis. The remote inspections cover the steam dryer, chimney, chimney head, core support structures, the peripheral CRD and incore housings. Access is provided to the reactor lower plenum for these inspections.

The analysis, design and equipment that are to be utilized for ESBWR comply with RG 1.20, as explained below.

RG 1.20 describes a comprehensive vibration assessment program for reactor internals during preoperational and initial startup testing. The vibration assessment program meets the requirements of Criterion 1, Quality Standards and Records, Appendix A to 10 CFR 50. This RG is applicable to the core support structures and other reactor internals.

Vibration testing of reactor internals is performed on all GE-BWR plants. Since the original issue of RG 1.20, test programs for compliance have been instituted for preoperational and startup testing. The first ESBWR plant is instrumented for testing. However, it can be subjected to startup flow testing only to demonstrate that FIVs similar to those expected during operation do not cause damage. Subsequent plants, which have internals similar to those of the first plant, are also tested in compliance with the requirements of RG 1.20. GEH is committed to confirm the satisfactory vibration performance of the internals in these plants through startup flow testing followed by inspection. Extensive vibration measurements in prototype plants together with satisfactory operating experience in all BWR plants have established the adequacy of reactor internal designs. GEH continues these test programs for subsequent plants to verify structural integrity and to establish the margin of safety. The FIV evaluation program pertaining to reactor internal components is addressed in Appendix 3L. As part of the initial implementation of the vibration assessment program, RG 1.20 guidance in Section 2.4 states that if inspection of the reactor internals reveals defects, evidence of unacceptable motion, or excessive or undue wear; if results from the measurement program fail to satisfy the specified test acceptance criteria; or if results from the analysis, measurement, and inspection programs are inconsistent, then further evaluations, modifications, or other actions are taken to justify the structural adequacy of the reactor internals. Such results and actions are reported to the NRC as part of the final report documentation of results of the comprehensive vibration assessment program following testing.

The Combined License (COL) Applicant will classify its reactor per the guidance in RG 1.20 and provide a milestone for submitting a description of the inspection and measurement programs to be performed (including measurement locations and analysis predictions) and the results of the vibration analysis, measurement and test program and address the recommendations in RG 1.20 for a comprehensive vibration assessment program for the steam dryer as described in Reference 3L-6 (COL 3.9.9-1-A).

3.9.2.5 Dynamic System Analysis of Reactor Internals Under Faulted Conditions

The faulted events that are evaluated are defined in Subsection 3.9.5.3. The loads that occur as a result of these events and the analysis performed to determine the response of the reactor internals are as follows:

(1) Reactor Internal Pressures — The reactor internal pressure differentials (Table 3.9-3) due to an assumed break of a main steamline (MSL) or feedwater line (FWL) are determined by analysis as described in Subsection 3.9.5.3. In order to assure that no significant dynamic amplification of load occurs as a result of the oscillatory nature of the blowdown forces during an accident, a comparison is made of the periods of the applied forces and the natural periods of the core support structures being acted upon by the applied forces. These periods are determined from comprehensive horizontal and vertical dynamic models of the

3.9.5 Reactor Pressure Vessel Internals

This subsection addresses the RPV internals as discussed in SRP 3.9.5. The RPV internals consist of all the structural and mechanical elements inside the reactor vessel. Safety-related structures and components are constructed and tested to quality standards commensurate with the importance of the safety-related functions to be performed, and designed with appropriate margins to withstand effects of AOOs, normal operation, natural phenomena such as earthquakes, postulated accidents including LOCA, and from events and conditions outside the nuclear power unit as discussed in GDC 1, 2, 4 and 10 and 10 CFR 50.55a.

The plant meets the requirements of the following regulations:

(1) GDC 1 and 10 CFR 50.55a, as they relate to reactor internals; the reactor internals are designed to quality standards commensurate with the importance of the safety-related functions to be performed.

(2) GDC 2, as it relates to reactor internals; the reactor internals are designed to withstand the effects of earthquakes without loss of capability to perform their safety-related functions.

(3) GDC 4, as it relates to reactor internals; reactor internals are designed to accommodate the effects of and to be compatible with the environmental conditions associated with normal operations, maintenance, testing, and postulated LOCA. Dynamic effects associated with postulated pipe ruptures are excluded from the design basis when analyses demonstrate that the probability of fluid system piping rupture is extremely low under conditions consistent with the design basis for the piping.

(4) GDC 10, as it relates to reactor internals; reactor internals are designed with appropriate margin to assure that specified acceptable fuel design limits are not exceeded during any condition of normal operation, including the effects of AOOs.

This subsection identifies and discusses the structural and functional integrity of the major RPV internals, including core support structures.

The core support structures and reactor vessel internals (exclusive of fuel, control rods, and in-core nuclear instrumentation) are as follows:

- Core Support Structures
  - shroud;
  - shroud support;
  - core plate (and core plate hardware);
  - top guide (and top guide hardware);
  - fuel supports (orificed fuel supports and peripheral fuel supports);
  - CRGTs; and
  - non-pressure boundary portion of CRDHs.
- Internal Structures (Components marked with an * are nonsafety-related.)
  - chimney* and partitions*;
  - chimney head* and steam separator assembly*;

- steam dryer assembly*;
- feedwater spargers*;
- SLC header and spargers and piping;
- RPV vent assembly*;
- in-core guide tubes and stabilizers;
- surveillance sample holders*; and
- non-pressure boundary portion of in-core housings.

A general assembly drawing of the important reactor components is shown in Figure 3.9-7.

The floodable inner volume of the RPV can be seen in Figure 3.9-2. It is the volume up to the level of the GDCS equalizing nozzles.

The design arrangement of the reactor internals, such as the shroud, chimney, steam separators and guide tubes, is such that one end is unrestricted and thus free to expand.

3.9.5.1 Core Support Structures

The core support structures consist of those items listed in Subsection 3.9.5 and are safety-related as defined within Section 3.2. These structures form partitions within the reactor vessel to sustain pressure differentials across the partitions, direct the flow of the coolant water, and locate and support the fuel assemblies. Figure 3.9-3 shows the reactor vessel internal flow paths.

Shroud

The shroud and chimney make up a stainless steel cylindrical assembly that provides a partition to separate the upward flow of coolant through the core from the downward recirculation flow. This partition separates the core region from the downcomer annulus. The volume enclosed by this assembly is characterized by three regions. The upper region or chimney surrounds the core discharge plenum, which is bounded by the chimney head on top and the top guide below. The central region of the shroud surrounds the active fuel. This section is bounded at the top by the top guide and at the bottom by the core plate. The lower region, surrounding part of the lower plenum, is welded to the support legs. The shroud provides the horizontal support for the core by supporting the core plate and top guide. A conceptual design of the connection between the shroud, chimney, and top guide is shown in Figure 3.9-8.

Shroud Support

The RPV shroud support is designed to support the shroud and the components connected to the shroud. The RPV shroud support is a ring supporting the core plate and series of vertical support legs supporting the ring. The support legs are welded to the vessel bottom head and the bottom of the support ring.

Core Plate

The core plate consists of a circular stainless steel plate with round openings. The core plate provides lateral support and guidance for the CRGTs, in-core flux monitor guide tubes, peripheral fuel supports, and startup neutron sources. The last two items are also supported vertically by the core plate. The core plate is bolted between the support ring and shroud. A conceptual design of the connection between the core plate, support ring and shroud is shown in Figure 3.9-9.

Top Guide

The top guide consists of a circular plate with square openings for fuel. Each opening provides lateral support and guidance for four fuel assemblies or, in the case of peripheral fuel, less than four fuel assemblies. Holes are provided in the bottom of the support intersections to anchor the in-core flux monitors and startup neutron sources. The top guide is mechanically attached to the top of the shroud and provides a flat surface for the chimney flange. The chimney is bolted to the top surface of the top guide as shown in Figure 3.9-8.

Fuel Supports

The Fuel supports (Figure 3.9-4) are of two basic types: peripheral supports and orificed fuel supports. The peripheral fuel supports are located at the outer edge of the active core and are not adjacent to control rods. Each peripheral fuel support supports one fuel assembly and contains an orifice designed to assure proper coolant flow to the peripheral fuel assembly. Each orificed fuel support holds four fuel assemblies vertically upward and horizontally and has four orifices to provide proper coolant flow distribution to each rod-controlled fuel assembly. The orificed fuel supports rest on the top a CRGT. The control rods pass through cruciform openings in the center of the orificed fuel support. This locates the four fuel assemblies surrounding a control rod. A control rod and the four adjacent fuel assemblies represent a core cell.

CRGTs

The CRGTs located inside the vessel extend from the top of the CRDHs up through holes in the core plate. Each guide tube is designed as the guide for the lower end of a control rod and as the support for an orificed fuel support. This locates the four fuel assemblies surrounding the control rod. The bottom of the guide tube is supported by the CRDH, which, in turn, transmits the weight of the guide tube, fuel support, and fuel assemblies to the reactor vessel bottom head. The CRGTs also include coolant flow holes near the top that are aligned with the coolant flow holes in the orificed fuel supports.

3.9.5.2 Internal Structures

The internal structures consist of those items listed in Subsection 3.9.5, and are safety-related or nonsafety-related as noted. These components direct and control coolant flow through the core or support safety-related and nonsafety-related functions.

Chimney and Partitions

These components are nonsafety-related internal components. The chimney is a long cylinder mounted to the top guide that supports the steam separator assembly. The chimney provides the driving head necessary to sustain the natural circulation flow. The chimney forms the annulus separating the subcooled recirculation flow returning downward from the steam separators and feedwater from the upward steam-water mixture flow exiting the core. The chimney cylinder is flanged at the bottom and top for attachment to the top guide and the chimney head, respectively. Inside the chimney are partitions that separate groups of 16 fuel assemblies. These partitions act to channel the mixed steam and water flow exiting the core into smaller chimney sections, limiting cross flow and flow instabilities, which could result from a much larger diameter open chimney. The partitions do not extend to the top of the chimney, thereby forming a plenum or mixing chamber for the steam/water mixture prior to entering the steam separators.

Chimney Head and Steam Separator Assembly

The chimney head and standpipes/steam separators are nonsafety-related internal components. The chimney head and steam separators assembly includes the upper flanges and bolts, and forms the top of the core discharge mixture plenum. The discharge plenum provides a mixing chamber for the steam/water mixture before it enters the steam separators. Individual stainless steel axial flow steam separators are supported on and attached to the top of standpipes that are welded into the chimney head. The steam separators have no moving parts. In each separator, the steam/water mixture rising through the standpipe passes through vanes that impart a spin and establish a vortex separating the water from the steam. The separated water flows from the lower portion of the steam separator into the downcomer annulus. The separator assembly is removable from the RPV on a routine basis.

Steam Dryer Assembly

The steam dryer assembly is a nonsafety-related component. The steam dryer removes moisture from the wet steam leaving the steam separators. The extracted moisture flows down the dryer vanes to the collecting troughs, then flows through drain ducts into the downcomer annulus.

The steam dryer assembly consists of multiple banks of dryer units mounted on a common structure, which is removable from the RPV as an integral unit. The dryer assembly includes the dryer banks, dryer supply and discharge ducting, drain collecting trough, drain duct, and a skirt that forms a water seal extending below the separator reference zero elevation. Upward and radial movement of the dryer assembly under the action of blowdown and seismic loads are limited by reactor vessel internal stops, which are arranged to permit differential expansion growth of the dryer assembly with respect to the RPV.

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 separator and 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.

Feedwater Spargers

These are nonsafety-related components. Each of two feedwater lines is connected to spargers through three RPV nozzles. The feedwater spargers deliver makeup water to the reactor during plant start up, power generation and plant shutdown modes of operation. The RWCU/SDC system and CRD system, upon low water level, also utilize the feedwater spargers.

The feedwater spargers are stainless steel headers located in the mixing plenum above the downcomer annulus. A separate sparger in two halves is fitted to each feedwater nozzle by a tee and is shaped to conform to the curve of the vessel wall. The sparger tee inlet is connected to the thermal sleeve arrangement. Sparger end brackets are pinned to vessel brackets to support the spargers. Feedwater flow enters the center of the spargers and is discharged radially inward to mix the cooler feedwater with the downcomer flow from the steam separators and steam dryer.

The feedwater also serves to condense steam in the region above the downcomer annulus and to subcool the water flowing down the annulus region.

SLC Header and Sparger and Piping

These are safety-related components. Each of two SLC nozzles feeds vertical piping extending down from the SLC nozzles to a header. Each header feeds two distribution lines extending down from the header to about the bottom of the fuel, and four injection lines with nozzles penetrating the shroud at four different levels (elevations). The injection lines enable the sodium pentaborate solution to be injected around the periphery of the core.

RPV Vent Assembly

This is designed as a nonsafety-related component. Only the piping external to the vessel is RCPB, and the vent function is a nonsafety-related operation.

The head vent assembly passes steam and noncondensable gases from the reactor head to the steamlines during startup and operation. During shutdown and filling for hydrostatic testing, steam and noncondensable gases may be vented to the drywell equipment sump while the connection to the steamline is blocked. When draining the vessel during shutdown, air enters the vessel through the vent.

In-Core Guide Tubes and Stabilizers

These are safety-related components. The guide tubes protect the in-core instrumentation from the flow of water in the bottom head plenum and provide a means of positioning fixed detectors in the core. The in-core flux monitor guide tubes extend from the top of the in-core flux monitor housing to the top of the core plate. The power range detectors for the power range monitoring units and the startup range neutron monitor detectors are inserted through the guide tubes. A conceptual design of the in-core guide tube and in-core monitor connection to the core plate is show in Figure 3.9-12.

A latticework of clamps, tie bars, and spacers give lateral support and rigidity to the guide tubes. A conceptual design of the In-core lateral supports is shown in Figures 3.9-10 and 3.9-11.

Surveillance Sample Holders

These are nonsafety-related components. The surveillance sample holders are welded baskets containing impact and tensile specimen capsules. The baskets hang from the brackets that are attached to the inside of the reactor vessel wall and extend to mid-height of the active core. The radial positions are chosen to expose the specimens to the same environment and maximum neutron fluxes experienced by the reactor vessel itself.

3.9.5.3 Loading Conditions

Events to be Evaluated

Examination of the spectrum of conditions for which the safety-related design bases (Subsection 3.9.5.4) must be satisfied by core support structures and safety-related internal components reveals three significant load events:

- RPV Line Break Accident — a break in any one line between the reactor vessel nozzle and the isolation valve (the accident results in significant pressure differentials across some of the structures within the reactor and RBV caused by suppression pool dynamics).
- Earthquake — subjects the core support structures and reactor internals to significant forces as a result of ground motion and consequent RBV.
- SRV or DPV Discharge — RBV caused by suppression pool dynamics and structural feedback.

The faulted conditions for the RPV internals are discussed in Subsection 3.9.1.4. Loading combination and analysis for safety-related reactor internals including core support structures are discussed in Subsection 3.9.5.4.

Reactor Internal Pressure Differences

For reactor internal pressure differences, the events at normal, upset, emergency and faulted conditions are considered.

The TRACG computer code is used to analyze the transient conditions within the reactor vessel following AOOs, infrequent events and accidents (e.g., LOCA). The analytical model of the vessel consists of axial and radial nodes, which are connected to the necessary adjoining nodes by flow paths having the required resistance and inertial characteristics. The program solves the energy and mass conservation equations for each node to give the depressurization rates and pressures in the various regions of the reactor.

In order to determine the maximum pressure differences across the reactor internals, a two sigma statistical uncertainty study is performed to determine the upper bound pressure difference adders that are applied to the nominal pressure differences.

Table 3.9-3 summarizes the maximum pressure differentials that result from the limiting events among the AOOs, infrequent events and accidents (e.g., LOCA).

Seismic and Other RBV Events

The loads due to earthquake and other RBV acting on the structure within the reactor vessel are based on a dynamic analysis methods described in Section 3.7.

Steam Dryer Acoustic Loading Effects from Safety-Relief Valve Standpipes and Main Steam Piping

The safety relief valves (SRVs) and safety valves (SVs) standpipes and main steam branch lines in the ESBWR are specifically designed to preclude first and second shear layer wave acoustic resonance conditions from occurring and to avoid pressure loads on the steam dryer at plant normal operating conditions. Appropriate selection of SRV standpipes vertical height between main steam piping and the valves, along with selection of valve entrance effects, minimizes vortex generation. Design of piping is based on Strouhal numbers outside the range for which adverse impacts due to acoustic resonance would occur (based on resonance frequency determined using velocity at the speed of sound). Calculations performed as described below show that design features and selections can acceptably eliminate first and second shear wave resonances in SRV/SV standpipes and main steam piping.

For standpipe configuration, main steam and SRV/SV configuration (dimensions and arrangement) and attachment of standpipes to the main steam piping are considered. System geometry and flow rates are used to calculate critical Strouhal ranges. Then the Strouhal values for flow at 100% and 102% power levels are calculated to ensure that the values at normal operating flow rates are not within the critical range and that additional margin is provided.

As shown on Figure 5.2-2, the ESBWR main steam system has two longer main steam lines with 5 SRV/SVs, and two shorter main steam lines with 4 SRV/SVs, mounted perpendicular to the main steam pipe centerline. For eliminating main steam flow acoustic frequency at branchline connections, boundary conditions at the connections are evaluated to ensure flow disturbances are not on the same order as acoustic waves that may pass through the system. Design features such as dimensions, diameter ratios, lengths of piping from reactor vessel nozzles, entrance effects, and flow rate effects are considered in the evaluation.

Acceptance criteria are to demonstrate through the evaluation that the final as-built design of 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. This is demonstrated by analysis showing that the final design maximum velocity, Strouhal range, and power level are outside the critical range of values where first and second shear resonances would occur. See Subsection 3.9.2.1 for piping vibration and dynamics effects testing during preoperational and startup testing. See NEDE-33313P (Ref. 3.9-7), Appendix B, for information regarding this design approach.

3.9.5.4 Design Bases

Safety-Related Design Bases

The reactor internals, including core support structures, meet the following safety-related design bases:

- The reactor vessel nozzles and internals are so arranged as to provide a floodable volume in which the core can be adequately cooled in the event of a breach in the nuclear system process barrier external to the reactor vessel.
- Deformation of internals is limited to assure that the control rods and core standby cooling systems can perform their safety-related functions.
- Mechanical design of applicable structures assures that the above safety-related design bases are satisfied so that the safe shutdown of the plant and removal of decay heat are not impaired.

Power Generation Design Bases

The reactor internals, including core support structures, are designed to the following power generation design bases:

- The internals provide the proper coolant distribution during all anticipated normal operating conditions to full power operation of the core without fuel damage.
- The internals are arranged to facilitate refueling operations.
- The internals are designed to facilitate inspection.

Design Loading Categories

The basis for determining faulted dynamic event loads on the reactor internals is shown in Section 3.7. Table 3.9-2 shows the load combinations used in the analysis.

Core support structures and safety class internals stress limits are consistent with the ASME B&PV Code, Subsection NG. For these components, Level A, B, C and D service limits are applied to the normal, upset, emergency, and faulted loading conditions, respectively, as defined in the design specification. Stress intensity and other design limits are discussed in the following paragraphs.

Stress and Fatigue Limits for Core Support Structures

The design and construction of the core support structures are in accordance with the ASME B&PV Code, Subsection NG.

Stress, Deformation, and Fatigue Limits for Safety Class and Other Reactor Internals (Except Core Support Structures)

For safety-related reactor internals, the stress deformation and fatigue criteria listed in Tables 3.9-4 through 3.9-7 are based on the criteria established in applicable codes and standards for similar equipment, by manufacturers' standards, or by empirical methods based on field experience and testing. For the quantity minimum safety factor (SF_{min}) appearing in those tables, the following values are used:

Service Level	Service Condition	SF_{min}
A	Normal	2.25
B	Upset	2.25
C	Emergency	1.5
D	Faulted	1.125

Components inside the RPV such as control rods, which must move during accident conditions, are examined to determine if adequate clearances exist during emergency and faulted conditions. The forcing functions applicable to the reactor internals are discussed in Subsection 3.9.2.

The design criteria, loading conditions, and analyses that provide the basis for the design of the safety class reactor internals other than the core support structures meet the guidelines of paragraph NG-3000 of the ASME B&PV Code and are constructed so as not to adversely affect the integrity of the core support structures (NG-1122).

The reactor internal structures classified as nonsafety-related in Section 3.9.5 are not ASME B&PV Code components, but their design complies with 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. Primary structural load bearing welds use quality and fatigue factors as given in NG-3000. The steam dryer assembly weld quality and fatigue factor methodology is discussed in Reference 3.9-7.

valve setup are measured. Depending on the valve and actuator type, these parameters may include seat load, running torque or thrust, valve travel, actuator spring rate, bench set and regulator supply pressure. Uncertainties associated with performance of these tests and use of the test results (including those associated with measurement equipment and potential degradation mechanisms) are considered appropriately. Uncertainties may be considered in the specification of acceptable valve setup parameters or in the interpretation of the test results (or a combination of both). Uncertainties affecting both valve function and structural limits are considered.

Additional valve testing may be performed by the plant licensee, for example, as part of the plant's air-operated valve program in response to Regulatory Issue Summary 2000-003 or as part of the plant's preventive maintenance program.

3.9.7 Risk-Informed Inservice Testing

Risk-informed inservice testing initiatives, if any, are included in the implementation plans for the IST Program, which is an operational program addressed in Section 13.4.

3.9.8 Risk-Informed Inservice Inspection of Piping

Risk-informed inservice inspection of piping initiatives, if any, are included in the implementation plans for the inservice inspection of piping program, which is an operational program addressed in Section 13.4.

3.9.9 COL Information

3.9.9-1-A Reactor Internals Vibration Analysis, Measurement and Inspection Program

The COL Applicant will:

(1) For the reactor internals, other than steam dryer, classify its reactor per the guidance in RG 1.20 and provide a milestone for submitting a description of the inspection and measurement programs to be performed (including measurement locations and analysis predictions) and the results of the vibration analysis, measurement and test program (Subsection 3.9.2.4).

(2) For the steam dryer, which is classified as a prototype per the guidance in RG 1.20, (a) provide a milestone of no later than 90 days before startup to prepare and provide to the NRC a Steam Dryer Monitoring Plan as described in NEDE-33313P (Ref. 3.9-7) Section 10; (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; (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; and (d) specify periodic steam dryer inspections during refueling outages (Subsection 3.9.2.4).

3.9.9-2-A ASME Class 2 or 3 or Quality Group D Components with 60-Year Design Life

The COL Applicant will provide a milestone for completing the required equipment stress reports, per ASME B&PV Code, Subsection NB, for equipment segments that are subject to loadings that could result in thermal or dynamic fatigue and for updating the FSAR, as necessary, to address the results of the analysis (Subsection 3.9.3.1).

3.9.9-3-A Inservice Testing Programs

The COL Applicant shall provide a full description of the IST Program and a milestone for full program implementation as identified in Subsection 3.9.6.1.

3.9.9-4-A A Snubber Inspection and Test Program

The COL Applicant shall provide a full description of the snubber preservice and inservice inspection and testing programs, and a milestone for program implementation, including development of a data table identified in Subsection 3.9.3.7.1(3)f (Subsection 3.9.3.7.1(3)e).

3.9.10 References

3.9-1 General Electric Company, "BWR Fuel Channel Mechanical Design and Deflection," NEDE-21354-P, September 1976 (GE proprietary) and NEDO-21354, September 1976 (Non-proprietary).

3.9-2 General Electric Company, "BWR Fuel Assembly Evaluation of Combined Safe Shutdown (SSE) and Loss-of-Coolant Accident (LOCA) Loadings (Amendment No. 3)," NEDE-21175-3-P-A, October 1984 (GE proprietary) and NEDO-21175-3-A, October 1984 (Non-proprietary).

3.9-3 General Electric Company, "General Electric Environmental Qualification Program," NEDE-24326-1-P, Proprietary Document, January 1983.

3.9-4 M.A. Miner, "Cumulative Damage in Fatigue," Journal of Applied Mechanics, Vol. 12, ASME, Vol. 67, pages A159-A164, September 1945.

3.9-5 American Society of Mechanical Engineers Code for Operation and Maintenance of Nuclear Power Plants, 2001 Edition with 2003 Addenda.

3.9-6 (Deleted)

*3.9-7 [GE Hitachi Nuclear Energy, "ESBWR Steam Dryer Structural Evaluation," NEDE-33313P, Revision ~~3~~5, Class III (Proprietary), ~~October~~ December ~~2010~~2013, and NEDO-33313, Revision ~~3~~5, Class I (Non-Proprietary), ~~October~~ December 201~~0~~3].**

3.9-8 American Society of Mechanical Engineers OM-S/G-1990, Standards and Guides for Operation and Maintenance of Nuclear Power Plants.

* References that are bracketed and italicized with an asterisk following the brackets are designated as Tier 2*. Prior NRC approval is required to change Tier 2* information.

Changes to ESBWR DCD due to Audit of the

ESBWR Steam Dryer Design Methodology

Changes For:

Tier 2, Chapter 3, “Design of Structures, Components, Equipment, and Systems”

Appendix 3L, “Reactor Internals Flow Induced Vibration Program”

including

Table 3L-5, “Applicable Data Reduction Method for Comparison to Criteria”

3L. REACTOR INTERNALS FLOW INDUCED VIBRATION PROGRAM

3L.1 INTRODUCTION

A flow-induced vibration (FIV) analysis and testing program of the reactor internal components of the ESBWR initial plant demonstrates that the ESBWR internals design can safely withstand expected FIV forces for reactor operating conditions up to and including 100% power and core flow. The ESBWR FIV program is considered to be a prototype per Reference 3L-1. This will require analysis, measurement and full inspection of reactor internals of the first plant. The ESBWR internals are similar to the Advanced Boiling Water Reactor (ABWR) internals; therefore, analyses and measurements from the ABWR FIV program are used to the extent possible. The ESBWR FIV program includes an initial evaluation phase that has the objective of demonstrating that the reactor internals are not subject to FIV issues that can lead to failures due to material fatigue. Throughout this part of the program, the emphasis is placed on demonstrating that the reactor components will safely operate for the design life of the plant. The results of this evaluation are shown in Reference 3L-1. This evaluation does not include the steam dryer since it is separately evaluated in References 3L-5, 3L-6, and 3L-8~~ and 3L-9~~; however, an overview of the steam dryer evaluation program is explained in Section 3L.4. The second phase of the program is focused on preparing and performing the startup test program that demonstrates through instrumentation and inspection that no FIV problems exist. This part of the program meets the requirements of Regulatory Guide 1.20 with the exception of those requirements related to preoperational testing that are not applicable to a natural circulation plant.

3L.2 REACTOR INTERNAL COMPONENTS FIV EVALUATION

The ESBWR reactor internals are part of an evolutionary Boiling Water Reactor (BWR) design, but fundamentally the components and function of the reactor vessel and internals are very similar to past BWRs. To a large extent, the ESBWR design of the components relies heavily on the prior design of internals in operating plants to assure that new vibration issues are not introduced. Also, to assure that the flow of steam or water in the reactor vessel is comparable to prior reactors, efforts were made to maintain traditional spacing and dimensional relationships of components. A unique feature of the ESBWR, with respect to FIV, is the fact that ESBWR is a natural circulation plant where no recirculation pumps exist that would create pressure pulses from the pump vanes that would travel into the reactor vessel. The recirculation pump's excitation has caused failures in components inside previous BWR reactor vessels. For the ESBWR this source of flow excitation does not exist. The ESBWR reactor internals are shown in Figure 5.3-3.

3L.2.1 Evaluation Process – Part 1

The first step in the evaluation process was to establish selection criteria for reactor internal components related to susceptibility to vibration. All reactor internal components were considered as potential candidates for further evaluation. Each component is evaluated against the following selection criteria:

- Is the component safety-related?
- Is the component of a significantly different or new design compared to earlier BWRs?

- Does the component have a history of FIV-related problems?
- Is the component subjected to significantly different or new flow conditions?

Based on these criteria, the following internal component structures are considered to be candidates for additional evaluation and potential to be instrumented in the startup FIV test program:

- Steam Dryer Bank Hoods and End Plates based on history of past FIV-related problems (e.g., fatigue cracking between hood and endplate).
- Steam Dryer Skirt based on history of past FIV-related problems (e.g., fatigue cracking between skirt and drain channels).
- Steam Dryer Drain Channels based on history of FIV-related problems (e.g., fatigue cracking between skirt and drain channels).
- Steam Dryer Support Ring based on history of FIV-related problems (e.g., steam dryer rocking).
- Chimney Assembly based on new design features (i.e., elongated Chimney Shell, Partition Assembly, Chimney Restraint), potential new flow conditions and limited ability to change the design due to dimensional and performance constraints.
- Chimney Head/Steam Separator assembly based on new design (i.e., shallow dished head or flat head with beam reinforcement, elongated standpipes and thinner stack materials).
- Shroud/Chimney Assembly based on new design features (see Figure 3.9-8), and potential new flow conditions.
- Standby Liquid Control (SLC) internal piping based on new design routed through the shroud and is safety-related.

Components that were evaluated and concluded to require no further evaluation:

- Control Rod Drive Housings
- Control Rod Guide Tubes
- In-Core Monitor Guide Tubes
- In-Core Monitor Housings

For each of these components, the length of the component has decreased from prior BWR product lines due to the plant having shorter fuel. This increases the natural frequencies for these components and moves the natural frequencies beyond the predominant frequencies measured at the prototype ABWR plant. Also, the flow velocities in the reactor pressure vessel (RPV) bottom head region have decreased and the calculated vortex shedding frequencies are well below the natural frequencies of the components in this region.

Other components such as the top guide and core plate that are not specifically identified as candidates for the instrumentation program are basically proven by trouble-free BWR experience, and have designs and flow conditions that are similar to prior operating BWR plants. Because most of the reactor internal components are large durable components where there has been no history of FIV issues, no FIV issues are anticipated. Also, because it is still early in the program, there is still the opportunity to make adjustments as necessary in the component designs to make them more resistant to FIV.

The results of the Part 1 evaluation are contained in Reference 3L-1.

The chimney assembly was a new component where only limited operating experience was available. Also, the chimney assembly is a structure where the geometry of the partitions places limitations on the plate thicknesses, has a long extended length, and is subject to high velocity two-phase steam flow. From this initial selection, a test and analysis program was established and the results are discussed in Subsection 3L.3.3. For this case, testing was required since no prior relevant test data was available for this component.

A steam dryer initial assessment was performed to study the acoustic and flow effects of the ESBWR configuration in comparison to the ABWR steam dryer design. The initial assessment determined that the increase in the size of the steam dryer support ring and skirt design and the increase in steam velocity did not have any adverse effects on the steam dryer structural integrity. However, at the time of the initial assessment, it was also recognized that the evaluation of BWR operating plant steam dryer loads was an ongoing program that would need to be ultimately factored into the ESBWR steam dryer design and evaluation effort. The progress of the replacement steam dryer program is now at a stage that a meaningful effort can now be planned for the ESBWR steam dryer. The detailed program that is planned is described in Section 3L.4. As a result of the advances in the understanding of steam dryer vibration, differential pressure loads and steam dryer design improvements (see Subsection 3L.2.3), the ESBWR uses a steam dryer design patterned after the ABWR and replacement steam dryer designs developed for BWR plants.

The SLC internal piping is based on a new design and is safety-related. The SLC line is in the downcomer flow field and is subject to vortex shedding flow induced vibration. The vibration characteristics of the SLC internal piping is evaluated as described in Section 3L.5.5.1.4. The SLC line is instrumented as part of the startup test program as shown in Table 3L-4.

3L.2.2 Evaluation Process – Part 2

The next phase of the evaluation program performed additional work to demonstrate the adequacy of the components where Part 1 determined additional evaluations were required. The objective of this phase completes a more quantitative evaluation and documents the existing facts regarding the individual components. This part of the evaluation focuses on the following:

(1) Similarities and differences of the ESBWR component design configurations as compared to prior designs. In most cases the comparison design is ABWR components.

(2) A review of prior calculations for the components being evaluated, to establish the mode shapes and natural frequencies. Calculation of the ESBWR component natural frequencies is determined based on this data.

(3) Prior plant startup instrumentation data from the prototype ABWR plant is reviewed to establish the magnitude and frequency of the measured vibration data, and to review the resulting calculated stress for the components that were instrumented.

(4) A comparison of the flow paths and characteristics of the ESBWR design to prior BWR designs where a startup vibration test program was conducted.

Using the results of the above items, an assessment as to the likelihood of FIV issues is completed and documented in Reference 3L-1. This report does not include the steam dryer since it was evaluated in separate reports (see references 3L-5, 3L-6, and 3L-8~~and 3L-9~~). The evaluations for the chimney components and SLC lines are included in this report, but alternate methods to those described above have been used to evaluate FIV since these are new BWR components. This report concludes that FIV evaluations have been completed and that none of the reactor internal components are susceptible to FIV.

During the evaluation phase, the process as identified in Subsection 3.9.2.3 was followed to prepare finite element analysis (FEA) models per the details shown in Subsection 3L.5.5.1. This information will then be used as the basis for the instrumentation in the ESBWR startup test program. It should be noted that the SLC internal piping, steam dryer and chimney have already been identified in Section 3L.2.1 for inclusion in the startup test program.

3L.2.3 Design and Materials Evaluation

FIV-related fatigue cracking and intergranular stress corrosion cracking are major causes of reactor internal component degradation observed in operating BWRs. The ESBWR reactor internals are designed to resist fatigue loading. Design evaluations are conducted to evaluate load paths and streamline structural discontinuities thus reducing stress risers that contribute to fatigue failure. Welds are reduced by integrating components through machining or castings. Some components are specifically designed for intersections between larger components so groove welds can be used in lieu of fillet welds. Design evaluations are also conducted to stiffen the component structure moving component fundamental frequencies above the frequency range associated with hydrodynamic and acoustic loads.

The reactor internal materials, as specified in Subsection 4.5.2, are resistant to corrosion and stress corrosion cracking in the BWR steam/water environment.

3L.3 CHIMNEY ASSEMBLY AND STANDBY LIQUID CONTROL INTERNAL PIPING EVALUATION

3L.3.1 Design and Materials

The chimney assembly design consists of a chimney shell and partition assembly. The chimney shell has a bottom ring that rests on the top guide (Figure 3.9-8). The chimney partitions rest on the top surface of the top guide. The top of the partition assembly is supported against the inside of the chimney shell. The partition assembly is a grid of square structures, each of which encompasses and lines up with four top guide fuel cells (i.e.,16 fuel assemblies). The chimney shell and partitions are fabricated using austenitic stainless steel plate (Table 4.5-1). The partitions are full length welded near the junctions of the partitions. The chimney shell that houses the partition structure is cylindrical, similar to the core shroud. A sketch of the chimney assembly is shown in Figure 3L-1. Because the chimney shell has structural characteristics similar to the shroud, this component is considered under the generic reactor internals vibration program, and the partition assembly is considered to be the unique component that requires special vibration consideration.

3L.3.2 Prior Operating Experience

Prior to the ESBWR design, the BWR-1 Dodewaard plant had operating experience with this chimney design, although it did not have a vibration instrumentation program. For this plant, the partition size was a square configuration that encompassed four fuel assemblies within the cell, which is ¼ the dimension of the ESBWR partitions. Also, the height was approximately ½ the length of the ESBWR design. The partition thickness was 3 mm (0.12 in) as compared to 9 mm (0.35 in) for ESBWR, and the partitions were welded together using intermittent fillet welds as compared to full-length groove welds in joints that are positioned away from the partition intersections for ESBWR. Although the partitions were not instrumented, the plant operated for almost 30 years without any issues related to the chimney structure. Since the design of the ESBWR chimney partitions is more fatigue-resistant, this Dodewaard operational history provides additional assurance that the ESBWR will not have FIV issues.

3L.3.3 Testing and Two-phase Flow Analysis

For the ESBWR, the chimney partition assembly constitutes a structure that has a unique vibration evaluation program as part of the ESBWR reactor internals. In order to assess its capability to maintain structural integrity under plant operating conditions, a flow induced vibration evaluation is performed in which the fluctuating fluid force acting on the partition plates is evaluated by a combination of scale tests and two-phase flow analysis.

The test scope comprised a 1/6-scale (100 mm × 100 mm [4 in x 4 in]), a 1/12-scale (50 mm × 50 mm [2 in x 2 in]) and one almost full scale (500 mm × 500 mm [20 in x 20 in]) chimney. Tests use a mixture of air and water to simulate two-phase flow testing inside the chimney. The velocities of the gas and liquid components of the two-phase flow were adjusted to be consistent with ESBWR values to simulate the actual two-phase flow pattern. Different inlet flow conditions in the smaller scale models were used to investigate the influence of inlet mixing within the partition to simulate different power conditions. Pressure fluctuation was measured on the inner surface of the partition wall with pressure transducers. The 1/6-scale model was later divided into four cells for investigating the pressure fluctuations between cells (Reference 3L-1).

The scale model tests were used to investigate the effect of model size on the magnitude of pressure fluctuations acting on the partition wall in steam-water conditions.

A structural analysis of the chimney and partition design was then conducted using finite element methods. First, an eigenvalue analysis determined that the lowest natural frequency of the chimney structure is approximately 54 Hz. This was sufficiently greater than the predominant frequency of pressure fluctuation determined by testing (2 Hz) that a static analysis of the structure was concluded to be proper. Based on the results of that static analysis, a maximum stress of 32.8 MPa (4,760 psi), with a fatigue strength reduction factor of 2, was calculated near the edge of the partition plate joint. This stress value is bounded by the allowable vibration ~~peak~~highest stress amplitude of 68.9 MPa (10,000 psi) specified in Subsection 3.9.2.3.

3L.3.4 SLC Internal Piping Evaluation

The SLC line is a new ESBWR component that enters the downcomer flow region at two locations, 180 degrees apart, in the annulus between the RPV and the chimney. The SLC piping continues down to the shroud where the piping divides and penetrates the shroud at two locations each. Since the configuration of the SLC line has a new geometry and location within the RPV, this component is analyzed and tested during initial startup.

A finite element beam model of SLC line was constructed and analyzed for FIV induced stresses (see Subsection 3L.5.5.1.4). The fundamental frequency of the SLC line was determined to be 31.2 Hz, which is well separated from the vortex shedding frequency of 5.5 Hz and, therefore, of no concern.

The SLC piping in the annulus is instrumented during startup of the first ESBWR. A summary description of these sensors is shown in Table 3L-4.

3L.4 STEAM DRYER EVALUATION PROGRAM

3L.4.1 Steam Dryer Design and Performance

The ESBWR steam dryer consists of a center support ring with dryer banks on top and a skirt below. A typical steam dryer is shown in Figure 3L-2. The dryer units, made up of steam drying vanes and perforated plates, are arranged in six parallel rows called dryer banks. The ESBWR steam flow rate is approximately 15% higher than ABWR. The ESBWR RPV has a larger inner diameter at the vessel flange than ABWR, which allows dryer banks to be extended, thereby accommodating the higher steam flow. The additional dryer unit face area results in approximately the same flow velocity through the drying vanes as ABWR and helps maintain moisture removal performance requirements. The support ring is supported by 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 is approximately mid-height on the steam dryer skirt.

Wet steam from the core flows upward from the steam separators into an inlet header, then horizontally through the inner perforated plate, the dryer vanes and the outlet perforated plates, then vertically in the outlet header and out into the RPV dome. Dry steam then exits the RPV through the steam outlet nozzles. Moisture (liquid) is separated from the steam by the vane surface and the hooks attached to the vanes. The captured moisture flows downward, under the force of gravity, to a collection trough that carries the liquid flow to vertical drain channels. The liquid flows by gravity through the vertical drain channels to the lower end of the skirt where the flow exists below the normal water level.

The prototype for the ESBWR steam dryer builds on the successful operating experience of the ABWR steam dryer. Although the ESBWR steam dryer will have a larger diameter and wider vane banks to accommodate close to 15% higher steam flow, the vane height, skirt length, outer hood setback from the main steam nozzle, and water submergence will be similar to the ABWR steam dryer. The ESBWR steam dryer also draws experience from operating plant replacement steam dryer program fabrication, testing and performance. Steam dryers recently tested and installed in BWR/3 plants had experienced high pressure loads under extended power uprate operating conditions. These loads were characterized by an abnormally high pressure tone at approximately 155 Hz that emanated from an acoustic resonance in one or more of the safety relief valve (SRV) standpipes. The replacement steam dryers were specifically designed to withstand the FIV and acoustic resonance loading that led to fatigue failures in the steam dryers for these plants. In addition, the SRV/SV standpipes and main steamline branch lines in ESBWR are specifically designed to preclude first and second shear layer wave acoustic resonances that could be a significant contributor to steam dryer loading at normal operating conditions. Table 3L-1 provides a comparison between major configuration parameters of the ESBWR, the ABWR prototype and a BWR/3 replacement steam dryer.

3L.4.2 Materials and Fabrication

Current industry and replacement steam dryer practices are applied to the materials and fabrication of the ESBWR steam dryer. The steam dryer materials are selected to be resistant to corrosion and stress corrosion cracking in the BWR steam/water environment, see Table 4.5-1.

3L.4.3 Load Combinations

Design loads for the steam dryer are based on evaluation of the ASME B&PV Code load combinations provided in Table 3.9-2 except that the load definitions that pertain to the steam dryer are modified as shown in Table 3L-2. These load combinations consist of deadweight loads, static and fluctuating differential pressure loads (including turbulent and acoustic sources), seismic, thermal, and transient acoustic and fluid impact loads.

3L.4.4 Fluid Loads on the Steam Dryer

During normal operation, the steam dryer experiences a static differential pressure loading across the steam dryer plates resulting from the pressure drop of the steam flow across the vane banks. The steam dryer also experiences fluctuating pressure loads resulting from turbulent flow across the steam dryer and acoustic sources in the vessel and main steamlines. During transient and accident events, the steam dryer also experiences acoustic and flow impact loads that result from system actions (e.g., turbine stop valve closure) or from the system response (e.g., the two-phase level swell following a main steamline break).

Of particular interest are the fluctuating acoustic pressure loads that act on the steam dryer during normal operation that have led to fatigue damage in previous steam dryer designs. In the low frequency range, these pressure loads have been correlated with acoustic sources driven by the steam flow in the outer hood and vessel steam nozzle region. In the high frequency range, acoustic resonances in the stagnant steamline side branches (e.g., relief valve standpipes) are coupled to the vessel, thus imparting a pressure load on the steam dryer. Vessel acoustic modes may also be excited by sources inside and outside the vessel, resulting in additional acoustic pressure loads in the middle frequency range.

A detailed description of the pressure load definition for the ESBWR steam dryer is provided in Reference 3L-5. The load definition is based on the Plant Based Load Evaluation Methodology described in Reference 3L-8. References 3L-8 ~~and 3L-9~~ provides the theoretical basis of the methodology, describes the analytical model and provides benchmark and sensitivity comparisons of the methodology predictions with measured pressure data taken from instrumented steam dryers. The fluctuating load definition is based on the load definitions based on in-plant measurements that were developed for the steam dryer structural analyses in several extended power uprates. These load definitions provide a fine-mesh array of pressure time histories that are consistent with the structural finite element model nodalization. Multiple load definitions are used in the ESBWR steam dryer analysis in order to evaluate the steam dryer response over a wide frequency range. These load definitions include the limiting low and high frequency loads observed in plants with instrumented steam dryers. Based on the unique plant configurations (e.g., dead legs in the main steamlines that may amplify the low frequency acoustic response) and operating conditions (e.g., high steam line flow velocities) in these instrumented plants, the load definitions from these plants are expected to provide a robust load definition for the ESBWR. The load definitions developed for the ESBWR are also benchmarked against the instrumented steam dryer measurements taken during startup testing for the lead ABWR. The ESBWR and ABWR have the same vessel diameter and vessel steam nozzle design (with flow restricting venturi), and similar main steamline layouts; therefore, it is expected that the frequency content of the ESBWR steam dryer pressure loads will be similar to those measured on the ABWR.

~~Reference 3L-9 provides the results of benchmarking and sensitivity studies of the pressure load definition methodology against measured pressure data taken during power ascension testing of a replacement steam dryer installed at an operating nuclear plant. Reference 3L-9 8 concludes that, based on comparisons of model predictions to actual measurements, the methodology predicts good frequency content and spatial distribution, and the safety relief valve resonances are well captured. The methodology provides accurate predictions of main steamline phenomena occurring downstream of the main steamline sensors, valve whistling (safety relief valve branch line) and broadband excitations (venturi, main steam isolation valve turbulence). The methodology also accurately predicts the dryer pressure loads resulting from vessel hydrodynamic phenomena.~~

3L.4.5 Structural Evaluation

A FEA is performed to confirm that the ESBWR steam dryer is structurally acceptable for operation. The FEA uses the load definitions described in Subsection 3L.4.4. The FEA is performed using a whole steam dryer analysis model to determine the most highly stressed locations, also see Subsection 3L.5.5.1.3. The FEA consists of dynamic analyses for the load combinations identified in Subsection 3L.4.3. If required, locations of high stress identified in the whole steam dryer analysis are further evaluated using solid finite element models to more accurately predict stresses at these locations. Additional analysis confirms that the RPV steam dryer support lugs accommodate the predicted loads under normal operation and transient and accident conditions. (Also see Subsection 3L.5.5.1.3.)

The structural evaluation of the ESBWR steam dryer design is presented in Reference 3L-6.

3L.4.6 Instrumentation and Startup Testing

The ESBWR steam dryer is instrumented with temporary vibration sensors to obtain flow induced vibration data during power operation. The primary function of this vibration measurement program is to confirm FIV load definition used in the structural evaluation is conservative with respect to the actual loading measured on the steam dryer during power operation, and to verify that the steam dryer can adequately withstand stresses from flow induced vibration forces for the design life of the steam dryer. The instrumentation and startup testing program for the ESBWR steam dryer follows NRC regulatory guidance in Reference 3L-10, as described below. The detailed objectives are as follows:

- Determine the as-built frequency response parameters: This is achieved by frequency response testing the steam dryer components. The results yield natural frequencies, mode shapes and damping of the components for the as-built steam dryer. These results are used to verify portions of the steam dryer analytical model.
- Confirm FIV loading: In order to confirm loading due to turbulence, acoustics and other sources, dynamic pressure sensors are installed on the steam dryer. These measurements will provide the actual pressure loading on the steam dryer under various operating conditions.
- Verify the design: Based on past knowledge gained from different steam dryers, as well as information gleaned from analysis, selected areas are instrumented with strain gages and accelerometers to measure vibratory stresses and displacements during power operation. The measured strain values are compared with the allowable values

(acceptance criteria) obtained from the analytical model to confirm that the steam dryer alternating stresses are within allowable limits.

The objective of the steam dryer frequency response test is to identify the as-built frequencies and mode shapes of several key components of the steam dryer at ambient conditions. Different components of the steam dryer have different frequencies and mode shapes associated with them. The areas of interest are the drain channel, the outer hood panel, the inner hood panel, the side panel, and the skirt. These results are used to verify portions of the finite element model of the steam dryer.

The concern is that local natural frequencies may coincide with existing forcing functions to cause resonance conditions. The resonance could cause high stresses to occur in localized areas of the steam dryer. A finite element frequency response analysis can calculate the frequency and mode shape of a component, but they are only ideal approximations to the real values due to variations such as plate thickness, weld geometries, configuration tolerances and residual stresses that affect the assumed boundary conditions in the finite element model. The mode shapes and frequencies determined by the frequency response test are used to validate the finite element frequency response analysis and determine the uncertainty in the finite element model predictions of the frequency response. The FE model and experimental transfer functions are then used to derive frequency dependent amplitude bias and uncertainty of the FE model for key areas of the dryer. This is described further in Reference 3L-6.

The frequency response test is performed following final assembly of the steam dryer. The tests are performed with the steam dryer resting on simulated support blocks similar to the way the steam dryer is seated inside the reactor vessel.

Two types of ~~impact~~ frequency response tests are performed on the steam dryer: (1) Dry frequency response test, and (2) Wet frequency response test with the steam dryer skirt and drain channels partially submerged in different water levels (to approximate in-reactor water level). Both tests are conducted in ambient conditions. Temporary bondable accelerometers are installed at predetermined locations for these tests. An instrumented input force is used to excite the steam dryer at several pre-determined locations and the input force and the structural responses from the accelerometers are recorded on a computer. The data is then used to compute experimental transfer functions mode shape, frequency and damping of the instrumented steam dryer components using appropriate software. The temporary sensors are then removed and the steam dryer is cleaned prior to installation in to the reactor vessel.

The steam dryer vibration sensors consist of strain gages, accelerometers and dynamic pressure sensors, appropriate for the application and environment. A typical list of vibration sensors with their model numbers is provided in Table 3L-3. The selection and total number of sensors is based on past experience of similar tests conducted on other BWR steam dryers. These sensors are specifically designed to withstand the reactor environment. The pressure instrument locations are selected to provide a good measure of the acoustic loading through the frequency range of interest. A proper distribution of the steam dryer pressure instruments facilitates accurate assessments of FIV loads. The layout of the steam dryer pressure instrument locations is evaluated using the RPV acoustic FEA Model. ~~The distribution of steamline instruments is determined using the Plant Based Load Evaluation model (Reference 3L-8) to provide an adequate measure of the acoustic loading through the frequency range of interest. The instrument layout permits steam dryer load development with steam dryer data alone, steamline~~

~~data alone, or a combination using both sets of data.~~ The approach used to determine the number and locations of pressure instruments is described in Subsections 2.3.2 and 4.4.2 of Reference 3L-8~~ and Subsections 4.4.3.1 and 4.4.4 of Reference 3L-9~~.

The steam dryer startup test and monitoring power ascension limits are developed on a similar basis as the monitoring limits used for recent extended power uprate replacement steam dryers. The power ascension limits are based on the final FIV analysis performed for the as-built steam dryer. Strain gages and accelerometers are used to monitor the structural response during power ascension. Accelerometers are also used to identify potential rocking and to measure the accelerations resulting from support and vessel movements. The approach used to determine the number and locations of the strain gages and accelerometers is described in Section 9.0 of Reference 3L-6. Specific information utilized to verify the FIV load definition during startup testing is described further in References 3L-5 and 3L-6.

Each of the sensors ~~are~~ is pressure tested in an autoclave prior to assembly and installation on the steam dryer. An uncertainty analysis is performed to calculate the expected uncertainty in the measurements.

Prior to initial plant start-up, strain gages are resistance spot-welded directly to the steam dryer surface. Accelerometers are tack welded to pads that are permanently welded to the steam dryer surface. Surface mounted pressure sensors are welded underneath a specially designed dome cover plate to minimize flow disturbances that may affect the measurement. The dome cover plate with the pressure transducer ~~are~~ is welded to an annular pad that is welded permanently to the steam dryer surface. The sensor conduits are routed along a mast on the top of the steam dryer and fed through the RPV instrument nozzle flange to bring the sensor leads out of the pressure boundary. Sensor leads are routed through the drywell to the data acquisition area outside the primary containment.

Pressure transducers and accelerometers are typically piezoelectric devices, requiring remote charge converters that are located in junction boxes inside the drywell. The data acquisition system consists of strain gages, pressure transducers and accelerometer signal conditioning electronics, a multi-channel data analyzer and a data recorder. The vibration data from all sensors is recorded on magnetic or optical media for post processing and data archival. The strain gages, accelerometer and pressure transducers are field calibrated prior to data collection and analysis. This calibration includes the addition of natural strain gauge factors based on the specific vendor supplied calibration sheets and their effects on the final stress tables. The locations of the gauges are more distributed than BWR EPU gauge locations. The locations are selected to avoid pressure nodes in the acoustic harmonic response for frequencies that contribute most heavily to loading in the dryer components with the highest stress. The final pressure transmitter locations are evaluated using the PBLE model with multiple combinations of Frequency Response Function (FRF) sets corresponding to different transmitter locations. The resulting data are used to find locations that provide redundancy and minimize singularities over the frequency ranges of interest, with special consideration at frequencies critical to high stress locations in the dryer. The sensitivity of locations to dimensional tolerances is also considered. Strain gauge manufacturer installation procedures are followed to duplicate previous installations. Care is taken to assure surface preparation (attachment surface area polish), spotweld welding energy, and weld strength recommendations are followed for each gauge. Applicable lessons learned from manufacturer's recommendation were also incorporated into the

GEH welding procedure specification. Furthermore, knowledge is passed to the welders by holding pre-job briefs and discussing the proper technique for applying the gauges, emphasizing the uniform placement of spot welds at approximately 0.7 – 0.8 mm intervals. Afterwards, the welders will practice on shims until peel tests are successfully completed. Quality Control personnel are present to accept the weld process. The temporary vibration sensors are removed after the first outage.

~~In addition to the instrumentation on the steam dryer, the main steamlines are instrumented in order to measure the acoustic pressures in the main steamlines.~~ The ~~main steamline pressure measurements with the~~ steam dryer pressure measurements are used as input to an acoustic model for determining the pressures acting on the steam dryer in order to provide a pressure load definition for use in performing confirmatory structural evaluations.

In addition to the elements described above, 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 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.

COL Information Item 3.9.9-1-A implements the vibration assessment program. For each of the regulatory positions above, the NRC guidance (Reference 3L-10) explains how the program is to be conducted, how the processes assure structural integrity of the steam dryer, and identifies information and reports that are to be prepared and when the information and reports should be submitted. Steps in the process for the regulatory positions include the following key elements:

Position 2.1: The steam dryer analysis and modeling methodologies for performing a vibration and stress analysis are described in References 3L-5, 3L-6, and 3L-8. NRC guidance specifies that a summary of the vibration analysis program should be submitted to the NRC at least 60 days prior to submission of the description of the vibration measurement and inspection programs (or 120 days if submitted with a description of the vibration measurement and inspection phases description). Thus, a summary of the as-built steam dryer structural analysis with the applied acoustic loads would be developed and submitted to the NRC. In addition, the supporting information will be available for NRC review for assuring acceptance criteria are met in accordance with ESBWR DCD Subsections 3.9 and 14.3. This analysis is used to correlate results obtained through vibration measurements during power ascension.

Position 2.2: Details of the steam dryer monitoring program are described above and in References 3L-5, 3L-6, and 3L-8. According to NRC guidance, a description of the vibration measurement and inspection phases of the comprehensive vibration assessment program should be submitted to the NRC in sufficient time to permit utilization of the staff's related recommendations (allowing 90 days for staff's review and comment period). This submittal would be focused on the as-built steam dryer monitoring and instrumentation to be used for obtaining vibration measurements, with details of the data acquisition and reduction system (e.g., transducer types, transducer position, measures to maximize quality of data, online data evaluation system, procedures, and bias errors associated with the instruments). During power ascension, the steam dryer instrumentation (strain gages, accelerometers and dynamic pressure transducers) is monitored against established limits to assure the structural integrity of the steam dryer is maintained. If resonant frequencies are identified and the vibrations increase above the pre-determined criteria, power ascension is stopped. The acceptability of the steam dryer for continued operation is evaluated by revising the load definition based on the measured loading, repeating the structural analysis using the revised load definition, and determining revised operating limits based on the results of the structural analysis.

~~It is expected that subsequent ESBWR units will be monitored using the main steam lines pressure data. Additional information on power ascension testing, acceptance criteria, benchmarking loads, and benchmarking of the FE model for the first and subsequent ESBWR units is included in references 3L-5 and 3L-6.~~

Position 2.3: Specific steam dryer inspection recommendations for the ESBWR steam dryer design are developed based on the final as-built design and structural analysis results. The steam dryer inspection recommendations are consistent with Reference 3L-2, and consistent with Boiling Water Reactor Vessel Internals Program guidance issued by the BWR owners group specific to reactor internals vibration. According to NRC guidance, a description of the inspection phase would be included in the submittal with a description of the vibration measurement program. This description would identify any inspections that are to be performed prior to and following operation during power ascension, and describe procedures and method of inspections, if any, of the steam dryer.

Position 2.4: According to NRC guidance, results of the comprehensive vibration assessment program should be reviewed and correlated to determine the extent to which test acceptance criteria are satisfied. The preliminary report following startup testing should compare preliminary comparison of data to test acceptance criteria and identify anomalous data that could bear on the steam dryer structural integrity. If results are acceptable, the final report should include a description of any deviations, comparison between measured and analytically determined modes of structural response and hydraulic response for verifying analytical technique, determination of margins of safety, and evaluation of unanticipated observations or measurements that exceeded acceptable limits not specified as test acceptance criteria (as well as disposition of such deviations). If testing or inspections reveal defects or unacceptable results, the final report should also include an evaluation and description of the modifications or actions planned to justify the structural adequacy of the steam dryer.

Position 2.5: A schedule for conducting the elements of the comprehensive vibration assessment program is inherent in COL Information Item 3.9.9-1-A. NRC guidance specifies that the steam dryer be classified as prototype or non-prototype; that a commitment be made in the DCD or

COL application regarding the scope of the comprehensive vibration assessment program; and that certain submittals be made describing the program and results with suggested schedules for the submittals.

With the detailed description above and implementation of COL Information Item 3.9.9-1-A, the instrumentation and startup testing program elements are consistent with NRC regulatory guidance and adequately ensure steam dryer structural integrity.

3L.5 STARTUP TEST PROGRAM

This section summarizes the program for preparing and performing the startup FIV testing including the methods and analysis that are performed when the startup test data is available. This section assumes that the initial selection of components identified in Subsection 3L.2.1 will be part of the analysis and instrumentation associated with the startup testing program.

Testing requirements of this program are incorporated into the Initial Test Program detailed in Section 14.2 through the Reactor Internals Vibration Test described in Subsection 14.2.8.2.11. The test procedure acceptance criteria, derived from the evaluations described in this appendix, are classified by definitions in the Startup Administrative Manual outlined in Subsection 14.2.2. Direction on the quality process to be used to control the resolution of test acceptance criteria failures is incorporated in the Startup Administrative Manual and specific guidance may be included in the test procedure.

3L.5.1 Component Selections

The components that are selected for instrumentation are determined from the initial evaluation phase as discussed in Subsection 3L.2.1. Many different sensors of four different types are utilized to measure vibration related data on several different reactor internal component structures.

3L.5.2 Sensor Locations

Having determined the components to instrument during the test, sensor locations on those structures are determined based upon the analytically predicted mode shapes for each structure, or calculated maximum stress locations or, sensor locations based on computational fluid dynamics modeling, and in some cases, based upon the location of past FIV-related failures. Strain gages and accelerometers are used for monitoring vibration levels. Strain gages measure local strain from which local stress can be calculated. Based on knowledge of the natural mode shapes of the structure or calculated stress distribution, ~~peak~~ highest stresses at other locations on the structure are determined from these data. Accelerometers (with double integration of the output signal) provide measurements of local structural displacement. This information, together with knowledge of the natural mode shapes of the structure or calculated stress distribution, allows the ~~peak~~ highest stresses to be calculated at other locations. Pressure sensors are also utilized at various locations in the vessel. These are not used to measure structural vibration directly, but rather to measure the pressure variation that is often a forcing function that causes the structural vibration. These pressure sensor data are very useful for determining the source of any excessive vibration amplitudes, if they are to occur during testing. Sensor types and locations are listed in Table 3L-4.

3L.5.3 Test Conditions

Test conditions are selected early in the FIV test program to consider a variety of steady-state and transient operating conditions that could be expected to occur during the life of the plant. Tests are identified in the Initial Test Program (ITP) schedule during heat up and power operation testing phases, when at steady-state conditions and with transient test sequences, as necessary. Specific conditions for testing are integrated into the initial startup by inclusion in the ITP schedule outlined in Subsections 14.2.2.4 and 14.2.7. Hold points and milestones are included to allow for test result review and approval, overall phase testing approval and authorization to proceed with the next testing phase documented in the Startup Administrative Manual, which includes time for COL Holder and NRC staff interactions.

RPV internals vibration at steady-state conditions is more important than transient conditions for evaluating the structural integrity of components. This is because steady-state normal operating conditions can exist for long periods of time, allowing a very large number of vibration cycles to accumulate. The FIV caused by transient operating conditions is far less influential because of the relatively low number of vibration cycles that occur over the lifetime of the plant. The purpose in including transient test conditions is to confirm that extremely high stresses do not occur during transients. This check is accomplished during the actual startup transient tests by the vibration engineers monitoring the test equipment. Transient stress levels near the allowable limit would be easily and immediately detected by the vibration engineers. No such high stress levels are expected to occur during the ESBWR initial plant FIV transient tests. Therefore, for the purposes of confirming the structural capability of the internals, steady-state test conditions are the most important conditions to evaluate.

Total volumetric core flow rate is also an important parameter that affects the vibration magnitude of the internals. Vibration amplitude generally increases as the volumetric flow rate increases.

3L.5.4 Data Reduction Methods

Basically, two types of data reduction are performed: (1) time history analyses and (2) spectrum analyses. In either data reduction method, the measured peak-to-peak (p-p) value of each sensor signal is compared to the allowable p-p value. Even though time history, spectrum analyses or both are performed for each selected sensor and test condition, the results from only one data reduction method are used for comparison to the allowable values. The selection of the method is dependent on the analysis method used for data evaluation. Table 3L-5 describes the method of data reduction that is applicable to each component.

3L.5.4.1 Time History Analysis

The time history method uses the analyzer's time capture mode of operation. Time capture is performed for a period of several minutes for all the selected sensors and test conditions. The frequency bandwidth for the time capture is chosen to accommodate 0-200 Hz as a minimum for most channels.

For comparison to the allowable vibration amplitude, the measured p-p value over specified bandwidths needs to be obtained for sensors in specific components. The bandwidths used for p-p measurements for various components are shown in Table 3L-5. There are six bandwidths for time history p-p measurement: 0-80 Hz, 0-200 Hz, 0-100 Hz, 80-200 Hz, 100-200 Hz and 0-1600 Hz. The 0-1600 Hz is used only for the accelerometer for the purpose of detecting impacts. The other three bandwidths are used for normal vibrations.

For the 0-200 Hz bandwidth, the maximum p-p values over several minutes of data for selected sensors and test conditions are obtained directly from the time capture. Specification of the bandwidth for time capture (0-200 Hz) automatically results in a low-pass filtered signal.

In order to obtain the maximum p-p in the 0-100 Hz range, the histogram operation is employed on the time capture traces. When the bandwidth (0-100 Hz) is specified in the histogram operation, the signal is automatically low-pass filtered in the specified frequency range. The histogram measurement shows how the amplitude of the input signal is distributed between its maximum and minimum values. The horizontal axis is the amplitude axis and usually the center of the horizontal axis is the zero point with positive and negative amplitudes on either side of the zero. The vertical axis is the number of counts or the number of times a particular amplitude value occurs in a time-history. From the histogram, the maximum positive and maximum negative values in a time history can be obtained, from which the maximum p-p of the time history can be obtained.

For the 100-200 Hz bandwidth range, the time captured traces are filtered in the 100-200 Hz range and the p-p is obtained over a period of several minutes. The filtered time history between 100 and 200 Hz is scanned to obtain maximum and minimum values to get p-p values.

For the 0-1600 Hz range for accelerometers, the time history signal is examined for the presence of any impacts.

3L.5.4.2 Frequency Analysis

The spectrum shows the signal in the frequency domain. There are several different types of spectra. The linear spectrum is the Fourier transform of the time history signal. The auto power spectrum is the magnitude squared of the linear spectrum, which is computed by multiplying the Fourier transform of the signal by its complex conjugate. This spectrum contains magnitude information only. The spectra generated for ESBWR data reduction are auto power spectra. The spectra for selected sensors and test conditions are obtained from the captured time history described previously.

Signal averaging is used to obtain better statistical properties. It is possible to select the number of averages and the type of averaging. There are three types of averaging:

- Stable (normal)
- Exponential
- Peak Hold

The averaging method used for ESBWR is “Peak Hold”, which compares the current spectral value of each individual frequency during the analysis interval to the last spectral value and holds the larger of the two. The resultant spectrum is a composite spectrum which envelopes the spectrums of all analysis intervals. The parameters used in the spectrum generation are described in Table 3L-6.

In order to obtain greater accuracy on amplitude of the frequency spectrum, a flat top window is selected.

From the spectrum, the dominant frequencies of vibration and their root mean square (RMS) magnitudes can be identified. The frequency is in the horizontal axis and the RMS magnitude is in the vertical axis. The p-p value of vibration at each dominant frequency is obtained by multiplying the RMS value (from the peak hold spectrum) by a factor of 6. This factor is obtained from many years of reactor experience and is a conservative estimate of the p-p value.

This p-p value is then used to compute the stress at the sensor location and the maximum stress in the structure.

3L.5.5 Data Evaluation Methods

This section describes the methods used to evaluate the reduced test data for the purpose of determining whether maximum stress levels are below the maximum allowable fatigue stress limits for the materials. A significant portion of this evaluation lies in the determination of the natural vibration modes of the instrumented components as determined using finite element models. Subsection 3L.5.5.1 describes the finite element models used in this process. Subsection 3L.5.5.2 describes the steps involved in determining the maximum stress amplitudes from the reduced data.

3L.5.5.1 Finite Element Models

Dynamic analytical finite-element models are developed for the following ESBWR plant reactor internal components:

- Chimney Head and Steam Separators
- Shroud and Chimney
- Steam Dryer
- SLC Line

The dynamic analytical finite-element models are used to predict the natural vibration frequency, modal displacement, and modal strain and stress for each of the dominant vibration response modes. Descriptions of the finite-element models are given in the following subsections.

3L.5.5.1.1 Chimney Head and Steam Separators

In order to determine the chimney head and steam separator vibration frequencies and mode shapes, a 3-dimensional model is developed using the ANSYS computer code (Reference 3L-3). The detailed model consists of the components that provide structural members within the assembly. Since the separator assembly units are the standard product used on prior BWR product lines, and that operates within the range of the design steam flow rates, detailed modeling is not required. In this model, each nodal point has four degrees of freedom, namely:

- radial displacement;
- tangential displacement;
- vertical displacement; and
- meridian rotation.

3L.5.5.1.2 Shroud and Chimney

In order to determine the shroud vibration frequencies and mode shapes, an axisymmetric shell model is developed using the ANSYS computer code (Reference 3L-3). The detailed shell model consists of both the RPV, chimney, chimney support, and shroud such that the hydrodynamic interaction effects between the components are accounted for. In this model, each nodal point has four degrees of freedom, namely:

- radial displacement;
- tangential displacement;
- vertical displacement; and
- meridian rotation.

The following assumptions are made in generating the axisymmetric shell model:

(1) Discrete components move in unison for steam separators, standpipes, and CRDHs and guide tubes.

(2) Masses are lumped at the nodal points. Rotational inertias of the masses are neglected.

(3) Stiffnesses of control rods, control rod drives, steam dryers, and in-core housings are neglected.

(4) Top guide and core plate masses are lumped to the shroud.

(5) Masses of CRDHs below the vessel are lumped to the bottom head.

Equivalent shells are used to model the mass and stiffness characteristics of the guide tubes, steam separators, and standpipes such that they match the frequencies obtained from a horizontal beam model.

Diagonal hydrodynamic mass terms are selected such that the beam mode frequencies of the shell model agree with those from the beam model.

The RPV, chimney and shroud are modeled as thin shell elements. The shell element data are defined in terms of thickness, mass density, modulus of elasticity, and Poisson's ratio for the appropriate material and temperature.

The natural frequencies and mode shapes of the shroud shell model are given in terms of two parameters, termed "n" and "m". The "n" parameter refers to the number of circumferential waves, while the "m" parameter refers to the number of axial half-waves. Thus, for beam types of vibration, n=1.

3L.5.5.1.3 Steam Dryer

The design of the steam dryer assembly for the ESBWR plant is similar to ABWR.

However, the total steam flow rate of the ESBWR plant is different from past designs. These differences warrant a detailed vibration analysis and test monitoring to assure the adequacy of the new design to withstand the FIV.

In the ABWR initial plant FIV test program of the steam dryer assembly, accelerometers were located on the cover plate and several locations on the skirt, and strain gages were located directly on the skirt, drain channels and hoods (Reference 3L-5). In addition, pressure sensors were used to measure the pressure differentials between the inside and outside of the upper skirt adjacent to the front hood and the lower skirt. The differential pressure fluctuation across the hoods and skirt is the primary forcing function causing vibration of the steam dryer structure.

A dynamic finite element model of the steam dryer assembly is developed using the ANSYS computer code (References 3L-3 and 3L-6). Due to the complicated geometry and the large size of the analytical model, major components may be modeled with coarse meshes such that their dynamic contributions are accounted for in the whole steam dryer assembly vibration responses. Separate refined dynamic finite element models of the major components are then developed to provide a high resolution of the component's response calculation.

The structural material properties and density for the steam dryer components at temperature are used in the model. The effect of the water on the dynamic responses is accounted for by explicitly modeling the dynamic properties of the fluid in the submerged portions of the skirt, drain channels, and the base ring.

Prior analytical models have predicted that the vibration modes are closely spaced. The final as-built structural predictive vibration analysis is performed prior to startup testing for correlation to final measurement results of acoustic loads measured on the steam dryer during startup testing, as elements of a comprehensive vibration assessment program described in Subsection 3L.4.6.

3L.5.5.1.4 Standby Liquid Control Lines

There are two SLC pipes that enter the reactor vessel and are routed to the shroud. To accurately predict the vibration characteristic of the SLC line, a dynamic finite element model of the entire line is developed. In the model, the ends of the line are fixed anchor points since the lines are welded at the vessel nozzle and the shroud attachment points. The SLC line is supported at six places. The top vertical segment is supported at the RPV at two places along its length; the horizontal circular segment is supported by two symmetrically placed supports at the shroud; and the two vertical segments in the bottom length are supported at the shroud by one support in each segment.

3L.5.5.2 Stress Evaluation

Table 3L-7 lists the methods that are used for each instrumented component for the FIV test program. Evaluation of all internals except the steam dryer is contained in this subsection; steam dryer structural evaluation is contained in Reference 3L-6. For this section, Method I is used for components that have many closely spaced natural vibration modes and utilizes the strain energy weighting method applied to all modes over the frequency range of interest. This method has previously been applied to the ABWR prototype plant startup tests of In-core Monitor housings, and shroud. Method II is similar to Method I, except that it is applied to two frequency bands, 0-100 Hz and 100-200 Hz. Method III is used for components that have relatively few, distinct dominant natural modes that are matched to the analytical modes. This method has previously been applied to the in-core guide tubes.

Maximum stress amplitude values for evaluation against allowable limits are determined from the test data and finite element models using one of three different evaluation methods. The method used for a particular component depends on the complexity of that component's vibration characteristics. Each of these methods yield conservatively high predictions of the maximum stress anywhere on the structure. These conservatively high stress predictions are compared against conservatively low acceptance criteria to assure that none of the components is experiencing high stress vibrations that might cause fatigue failures. The acceptable fatigue limit stress amplitude for the reactor internals component material is 68.9 MPa (10,000 psi), with the exception of the steam dryer.

Method I is used for components that have many closely spaced vibration frequencies or closely spaced natural vibration modes distributed over a relatively narrow frequency range. The method utilizes a strain energy weighting method applied to all modes over the entire frequency range. It is applied by determining the maximum p-p amplitude from an unfiltered time history segment. This maximum value is multiplied by a combined shape factor (derived from the strain energy weighting method) and stress concentration factors (SCFs) to yield the maximum stress value that could be expected to be found anywhere on the structure. This value is then compared against the acceptable fatigue limit stress amplitude for the component and material.

Method II is used for components that have many closely spaced vibration frequencies or closely spaced natural vibration modes that are unevenly distributed over several frequency ranges. The method is very similar to Method I, except that it is applied over several separate frequency bands. The maximum stress amplitude values for each frequency band are then added together absolutely to yield a conservatively high value for the overall maximum stress amplitude that could be found anywhere on the structure. This value is then compared against the acceptable fatigue limit stress amplitude for the component and material.

Method III is used for components that have relatively few, distinct dominant natural modes that can be easily identified and matched to the modes predicted by the finite element models. This method utilizes a mode shape factor for each vibration mode that relates the stress at the sensor location to the stress at the maximum stress location for that mode. Appropriate SCFs are also considered in this process. Response spectra are generated from the sensor output, from which the equivalent maximum p-p strain amplitude for each mode can be determined. The mode shape and SCFs are applied mode by mode to determine the maximum stress amplitude associated with each mode. Then the maximum stress amplitudes from each of the modes are added together absolutely to yield a conservatively high maximum overall stress amplitude for the structure. This value is then compared against the acceptable fatigue limit stress amplitude for the component and material.

These methods have identical initial steps to obtain mode shape factors for each natural mode. The steps for these methods are as follows: (Note: The evaluation method described here relates to strain gages. Similar steps are used for accelerometers used in their displacement mode. The example assumes a maximum allowable stress amplitude for the material of 68.9 MPa (10,000 psi) for the purposes of illustration.)

(1) The dynamic finite element model of each instrumented component is used to predict the natural vibration modal displacement, frequency and stress for each vibration response mode. Specifically, the computer model provides the following results for each mode:

ω_i = Natural frequency for vibration mode i

$\{\phi\}_i$ = Mass normalized displacement mode shape for vibration mode i.

(Normalized such that the generalized mass, $\{\phi\}_i^T[M]\{\phi\}_i$, is unity, where [M] is the mass matrix.)

$\{\sigma\}_i$ = Normalized stress distribution for vibration mode i.
(The stress corresponding to the mass normalized mode shape, $\{\phi\}_i$)

The theory and methods for calculation of these parameters may be found in text books on the subject of basic vibration analysis, such as Reference 3L-4.

(2) For each vibration mode, SCFs are applied at weld locations and regions with high stress gradient. From this information, the maximum stress intensity location and value is determined for each vibration mode.

$\sigma_{i,\max} = Max\{SCF_i \cdot \sigma_i\}$ considered over the entire structure

where

SCF_i = Stress concentration factor at some location

σ_i = Normalized stress intensity at the same location

$\sigma_{i,\max}$ = Normalized maximum stress intensity for mode i

(3) From the stress distribution of Step 1, a mode shape factor is derived relating the stress at the sensor to the stress at the maximum stress location as determined in Step 2:

$$MSF_i = \frac{\sigma_i\,\text{(at maximum stress intensity location)}}{\sigma_{i,\text{sensor}}}$$

where

MSF_i = Mode shape factor

$\sigma_{i,sensor}$ = Normalized stress at sensor location for vibration mode i

(4) The mode shape factor from Step 3 and the maximum allowable stress amplitude for the material [68.9 MPa (10,000 psi)] are used to determine the maximum allowable stress value at the sensor location for each mode.

$$\sigma_{i,sensor,allowed} = \frac{68.9\,MPa}{(MSF_i)\cdot(SCF_i)}$$

where

$\sigma_{i,sensor,allowed}$ = Maximum allowed zero to peak stress amplitude at sensor location for vibration mode i (stress amplitude at sensor when maximum stress amplitude in structure is 68.9 MPa)

(5) The allowable strain for mode i ($\varepsilon_{i,\text{allowed}}$) is then calculated from this maximum allowed stress amplitude at the sensor location:

$$\varepsilon_{i,allowed} = \frac{\sigma_{i,sensor,allowed}}{E}$$

where

E = Young's modulus [e.g., 1.86×10^5 MPa (27.0×10^6 psi) at 160°C (320°F)]

This equation is for uniaxial stress components.

At this point, Methods I and II diverge from Method III.

3L.5.5.2.1 Methods I and II

The next two steps are identical for Methods I and II.

(1) A weighting factor is determined by the strain energy method, which begins by obtaining the solution to the following equation based on the expected forcing function:

$$\{U\} = q_1\{\phi\}_1 + q_2\{\phi\}_2 + \ldots = \sum_{i=1}^{N} q_i\{\phi\}_i$$

where

$\{U\}$ = A vector representing the displacement response of the structure when subjected to the expected forcing function shape. This displacement response to an input forcing function is calculated from the finite element model on the computer.

$\{\phi\}_i$ = Mass normalized mode shape for vibration mode i. Mode shapes were determined from modal analysis of the finite element model. The mode shapes are normalized such that the generalized mass, $\{\phi\}_i^T[M]\{\phi\}_i$, is unity (where [M] is the mass matrix).

q_i = Mode i response, dependent on load distribution. These coefficients are calculated from the previously calculated $\{U\}$ and $\{\phi\}_i$ using formulas derived from the generalized Fourier Theorem.

This is an application of the generalized Fourier Theorem, which establishes that a displacement function such as $\{U\}$ can be represented by a linear sum of the eigenfunctions, $\{\phi\}_i$. The theory and methods for calculation of these coefficients may be found in text books on the subject of basic vibration analysis, such as Reference 3L-4.

(2) The strain energy contribution, e_i, for each mode is then calculated:

$$e_i = \frac{1}{2} \cdot q_i^2 \cdot \{\phi\}_i^T \cdot [K] \cdot \{\phi\}_i$$

where

[K] = The structural stiffness matrix (For a more detailed explanation of the theory and calculation methods, see text books on the subject vibration analysis, such as Reference 3L-4.)

(3) This step is similar for both Methods I and II, the only difference being that Method I includes the entire frequency range in one group, while Method II uses several groups of frequency ranges. Then the strain energy weighted allowable strain vibration amplitude is calculated over a given frequency range by combining the weighted strain allowable values for each mode as follows:

For

$$\omega_I < \omega_1, \omega_2, \ldots, \omega_n \le \omega_{II}$$

$$\varepsilon_{II,allowed} = \frac{e_1 \cdot \varepsilon_{1,allowed} + e_2 \cdot \varepsilon_{2,allowed} + \ldots + e_n \cdot \varepsilon_{n,allowed}}{e_1 + e_2 + \ldots + e_n}$$

where

$\varepsilon_{II,allowed}$ = Allowable strain value between ω_I and ω_{II}, which includes the SCF

It should be noted that this step conservatively assumes that the ~~peak~~ highest stress of each mode occurs at the same physical location on the structure. In reality, the maximum stress locations for different modes may occur at different locations. Since the purpose of this calculation is just to confirm that the maximum stress is less than an acceptable limit, it is quite acceptable to add this conservatism. However, it should be understood that the value calculated is conservatively high, and it is not an accurate prediction of the actual stress amplitude. If a stress calculated in this manner should exceed the limit in a few situations, then a less conservative calculation can be used in those few cases.

The strain value in the above equation is the allowable strain used during the actual execution of the test. It represents the strain level at the sensor location when the maximum stress on the structure is 68.9 MPa (10,000 psi).

(4) Step 9 is the same for both Methods I and II, except that it is applied to each of the multiple frequency ranges associated with Method II; whereas, Method I is only for one frequency range. The combined shape factor is derived to relate the maximum zero-to-peak strain value measured at the sensor location to the corresponding maximum zero-to-peak stress intensity value on the structure.

$$\sigma_{II,\max} = \frac{\varepsilon_{II,measured,\max}}{\varepsilon_{II,allowed}} \cdot (68.9MPa) = \varepsilon_{II,measured,\max} \cdot CSF$$

where

$CSF = \dfrac{(68.9\ MPa)}{\varepsilon_{II,allowed}}$ = Combined Shape Factor with the SCF included.

$\sigma_{II,max}$ = Maximum zero-to-peak stress value anywhere on the structure for modes within the frequency range of ω_I to ω_{II}.

$\varepsilon_{II,measured,max}$ = Maximum measured zero-to-peak strain (one-half of maximum measured p-p) from time history of sensor band pass filtered over the frequency range ω_I to ω_{II}.

This is the maximum zero-to-peak stress value anywhere on the structure as determined by Method I. For Method I, this value is compared to 68.9 MPa (10,000 psi) for determination of acceptability.

(5) One additional step remains for Method II. The maximum stress values for each frequency band are added together using the absolute sum method to determine the overall maximum stress on the structure for comparison to the 68.9 MPa (10,000 psi) limit for the material.

$$\sigma_{MAX} = \sigma_{II,\max} + \sigma_{III,\max} + \ldots + \sigma_{N,\max}$$

where

σ_{MAX} = Maximum overall zero-to-peak stress anywhere on structure as determined by Method II.

$\sigma_{N,max}$ = Maximum zero-to-peak stress anywhere on structure within the frequency range of ω_{N-1} to ω_N (N-1 frequency ranges total).

σ_{MAX} is compared to the 68.9 MPa (10,000 psi) limit in order to determine acceptability under Method II.

It should be noted that this step conservatively assumes that the ~~peak~~ highest stress of each mode occurs at the same time. In reality, the maximum stress occurs at different times. Since the purpose of this calculation is just to confirm that the maximum stress is less than an acceptable limit, it is quite acceptable to add this conservatism. However, it should be understood that the value calculated is conservatively high, and it is not an accurate prediction of the actual stress amplitude. If a stress calculated in this manner should exceed the limit in a few situations, then a less conservative calculation can be used in those few cases.

3L.5.5.2.2 Method III

Method III uses the mode shape factor from Step 3, the SCF and the measured strain value to determine the maximum stress amplitude anywhere on the structure for each natural mode. Picking up after Step 5 from Subsection 3L.5.5.2:

(1) Maximum stress in the structure is calculated from the measured strain value at the sensor location.

$$\sigma_{i,MAX} = \varepsilon_{i,measured,\max} \cdot E \cdot MSF_i \cdot SCF_i$$

where

$\sigma_{i,MAX}$ = Maximum zero-to-peak stress anywhere on structure for mode i.

$\varepsilon_{i,measured,max}$ = Maximum zero-to-peak strain for mode i as determined from power spectrum from sensor signal.

E = Young's Modulus

MSF_i = Mode Shape Factor for mode i.

SCF_i = Stress Concentration Factor as applicable for maximum stress location for mode i.

(2) The maximum stress values for each mode are added together using the absolute sum method to determine the overall maximum stress on the structure for comparison to the 68.9 MPa (10,000 psi) limit for the material.

$$\sigma_{MAX} = \sigma_{1,MAX} + \sigma_{2,MAX} + \ldots + \sigma_{n,MAX}$$

where

σ_{MAX} = Maximum overall zero-to-peak stress anywhere on structure as determined by Method III.

$\sigma_{i,MAX}$ = Maximum zero-to-peak stress anywhere on structure for mode i (n total dominant modes).

σ_{MAX} is compared to the 68.9 MPa (10,000 psi) limit in order to determine acceptability under Method III.

It should be noted that this step conservatively assumes that the ~~peak~~ highest stress of each mode occurs at the same physical location on the structure and at the same time. In reality, the maximum stress locations for different modes may occur at different locations and at different times. Since the purpose of this calculation is just to confirm that the maximum stress is less than an acceptable limit, it is quite acceptable to add these conservatisms. However, it should be understood that the value calculated is conservatively high, and it is not an accurate prediction of the actual stress amplitude. If a stress calculated in this manner should exceed the limit in a few situations, then a less conservative calculation can be used in those few cases.

In summary, all three methods involve two significant conservatisms:

- The assumption of the maximum stresses occurring at the same location in a component, and
- The assumption that the maximum stresses for different modes occur at the same time.

Inclusion of these two significant conservatisms results in significantly higher calculated stresses.

3L.5.5.3 (Deleted)

3L.6 REFERENCES

3L-1 GE Hitachi Nuclear Energy, "Reactor Internals Flow Induced Vibration Program", NEDE-33259P-A, Revision 3, Class III (Proprietary), October 2010, and NEDO-33259-A, Revision 3, Class I (Non-proprietary), October 2010.

3L-2 General Electric Company, "BWR Steam Dryer Integrity", Service Information Letter (SIL) 644 Revision 2, August 30, 2006.

3L-3 ANSYS Engineering Analysis System User's Manual, see Table 3D.1-1 for the applicable revision.

3L-4 Elements of Vibration Analysis, Leonard Meirovitch, McGraw Hill Book Co., 1975.

3L-5 *[GE Hitachi Nuclear Energy, "Steam Dryer - Acoustic Load Definition," NEDE-33312P, Revision ~~3~~5, Class III (Proprietary), ~~February~~December 201~~0~~3, and NEDO-33312, Revision~~3~~ ,5 Class I (Non-Proprietary), ~~February~~ December 201~~0~~3.]**

3L-6 *[GE Hitachi Nuclear Energy, "Steam Dryer - Structural Evaluation," NEDE-33313P, Revision ~~3~~5, Class III (Proprietary), ~~February~~ December ~~2010~~2013, and NEDO-33313, Revision ~~3~~5, Class I (Non-Proprietary), ~~February~~ December ~~2010~~2013.]**

3L-7 (Deleted)

3L-8 *[GE Hitachi Nuclear Energy, "ESBWR Steam Dryer – Plant Based Load Evaluation Methodology, PBLE01 Model Description," NED~~C~~E-33408P, Revision ~~2~~5, Class III (Proprietary), ~~February~~December- 201~~0~~3, and NEDO-33408, Revision ~~2,~~5 Class I (Non-proprietary), ~~February~~ December 201~~0~~3]**.

3L-9 (Deleted)

~~GE Hitachi Nuclear Energy, "ESBWR Steam Dryer – Plant Based Load Evaluation Methodology Supplement 1," NEDC-33408, Supplement 1P-A, Revision 2, Class III (Proprietary),~~

~~October 2010, and NEDO-33408, Supplement 1-A, Revision 2, Class I (Non-Proprietary), October 2010.~~

3L-10 Regulatory Guide 1.20, "Comprehensive Vibration Assessment Program For Reactor Internals During Preoperational and Initial Startup Testing," Revision 3, March 2007.

* References that are bracketed and italicized with an asterisk following the brackets are designated as Tier 2*. Prior NRC approval is required to change Tier 2* information.

Table 3L-5

Applicable Data Reduction Method for Comparison to Criteria(2)(3)

Component	Sensor Type	Applicable Data Reduction Method	Frequency Bandwidth (Hz)(1)
Shroud	Strain Gages	Time History	0-100
Steam Dryer Skirt	Strain Gages	Time History	0-200
Steam Dryer Skirt	Accelerometer (Displacement)	Time History	0-100
Steam Dryer Drain Channels	Strain Gages	Time History	0-100, 100-200
Steam Dryer Hoods	Strain Gages	Time History	0-100, 100-200
Steam Dryer Support Ring	Accelerometer	Time History	0-1600 0-80, 80-200
Separator Top	Accelerometer	Time History	0-100
Chimney	Accelerometer	Time History	0-200
Standby Liquid Control Lines	Strain Gages, Accelerometer	Time History	0-100

(1) It should be noted that the 200 Hz frequency range is approximate and is dependent on the SRV standpipe design. The frequency range monitored and evaluated in the FIV test program is adjusted to bound the range of frequencies determined for the final SRV standpipe design.

(2) Pressure sensors data reduction from steam dome, steam dryer skirt, and steam dryer hood are not included in this table. The pressure data from these components ~~and the main steamlines~~ are discussed in Subsection 3L.4.6.

(3) For Method III, the spectrum method may be used in place of the Time History Method in cases with sufficient margin.