GE Energy

James C. Kinsey
Project Manager, ESBWR Licensing

PO Box 780 M/C J-70
Wilmington, NC 28402-0780
USA

T 910 675 5057
F 910 362 5057
jim.kinsey@ge.com

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Subject: **Response to Portion of NRC Request for Additional Information Letter No. 67 Related to ESBWR Design Certification Application – Nuclear Steam Supply Systems – RAI Numbers 3.9-58, 3.9-61 through 3.9-64, 3.9-66, 3.9-71, 3.9-133, 3.9-135 through 3.9-139, 3.9-141, 3.9-146**

Enclosure 1 contains GE's response to the subject NRC RAIs transmitted via the Reference 1 letter.

If you have any questions or require additional information regarding the information provided here, please contact me.

Sincerely,

Kathy Sedney for

James C. Kinsey
Project Manager, ESBWR Licensing

D068

Reference:

1. MFN 06-378, Letter from U.S. Nuclear Regulatory Commission to David Hinds, *Request for Additional Information Letter No. 67 Related to ESBWR Design Certification Application,* October 10, 2006

Enclosure:

1. MFN 07-194 – Response to Portion of NRC Request for Additional Information Letter No. 67 Related to ESBWR Design Certification Application – Nuclear Steam Supply Systems – RAI Numbers 3.9-58, 3.9-61 through 3.9-64, 3.9-66, 3.9-71, 3.9-133, 3.9-135 through 3.9-139, 3.9-141, 3.9-146

cc:	AE Cubbage	USNRC (with enclosures)
	DH Hinds	GE (with enclosures)
	RE Brown	GE (w/o enclosures)
	eDRF	0000-0065-8639

Enclosure 1

MFN 07-194

Response to Portion of NRC Request for Additional Information Letter No. 67

Related to ESBWR Design Certification Application

Nuclear Steam Supply Systems

RAI Numbers 3.9-58, 3.9-61 through 3.9-64, 3.9-66, 3.9-71, 3.9-133, 3.9-135 through 3.9-139, 3.9-141, 3.9-146

NRC RAI 3.9-58

There is no discussion in DCD Tier 2, Section 3.9.2.3 relative to the acoustic and computational fluid dynamic analyses to predict stresses at the locations to be monitored in the steam dryer. The applicant is requested to discuss the acoustic and computational fluid dynamic analyses to predict stresses at the locations to be monitored in the steam dryer.

GE Response

The steam dryer acoustic load definition process is described in Subsection 3L.4.4 of DCD, Tier 2, Appendix 3L. A more detailed discussion of the source of the load definition and validation of the load definition methodology will be provided in a future reference report: Reference 3L-5: General Electric Company, "Steam Dryer - Acoustic Load Definition," NEDC-33312P, Class III (Proprietary), and NEDO-33312, Class I (Non-Proprietary).

The steam dryer structural evaluation is described in Subsection 3L.4.5 of DCD, Tier 2, Appendix 3L. The steam dryer stress analysis and comparison to acceptance criteria will be provided in a future reference report: General Electric Company, "Steam Dryer - Structural Evaluation," NEDC-33313P, Class III (Proprietary), and NEDO-33313, Class I (Non-Proprietary).

The steam dryer instrumentation and startup testing process is described in Subsection 3L.4.6 of DCD, Tier 2, Appendix 3L. Details regarding the confirmation of the steam dryer load definition and stress analysis during initial power ascension will be provided in a future reference report: General Electric Company, "Steam Dryer - Instrumentation and Power Ascension Monitoring," NEDC-33314P, Class III (Proprietary), and NEDO-33314, Class I (Non-Proprietary). Computational fluid dynamic analyses are not used in the steam dryer acoustic load definition.

DCD Impact

DCD Tier 2, Subsections 3.9.2.3, 3.9.2.4 3L.4.5, 3L.5.5.1.3 and Section 3L.6 were revised as noted in the attached DCD Tier 2 Rev. 3 markup.

LTRs NEDE-33312P Rev 0, NEDO-33312P Rev 0, NEDE-33313P Rev 0, NEDO-33313P Rev 0, NEDE-33314P Rev 0 and NEDO-33314P Rev 0 were added in DCD Tier 2 Rev. 3 as noted in the attached markup.

NRC RAI 3.9-61

It is stated in DCD Tier 2, Section 3.9.2.4 that accelerometers are provided with double integration signal conditioning to give a displacement output. A partial list of the sensor locations has been provided. It is not clear from the list whether or not instrumentation will be mounted directly on the steam dryer at all significant locations including the outer hood, skirt and all potential high stress areas. Provide this additional information.

GE Response

The steam dryer will be instrumented with strain gauges and accelerometers to provide vibration measurements during startup testing. In addition, the steam dryer will be instrumented with dynamic pressure sensors to confirm the acoustic load definition used in the structural analysis. The steam dryer instrumentation and startup testing process is described in Subsection 3L.4.6 of DCD, Tier 2, Appendix 3L.

DCD Impact

DCD Tier 2, Subsection 3.9.2.4 was revised as noted in the attached DCD Tier 2 Rev. 3 markup.

NRC RAI 3.9-62

The discussion provided in DCD Tier 2, Section 3.9.2.4 does not specifically address the steam dryer instrumentation and its capabilities. There is also no discussion on what data would be obtained from these sensors for a stress analysis of the steam dryer and main steam system components. Provide a discussion to demonstrate that the instrumentation mounted directly on the steam dryers shall provide sufficient information to perform an accurate stress analysis of all steam dryer and main steam system components and would include appropriate pressure sensors, strain gauges, and accelerometers.

GE Response

The steam dryer will be instrumented with strain gauges and accelerometers to provide vibration measurements during startup testing. In addition, the steam dryer will be instrumented with pressure sensors to confirm the acoustic load definition used in the structural analysis. The steam dryer instrumentation and startup testing process is described in Subsection 3L.4.6 of the DCD, Tier 2, Appendix 3L. Additional reference reports will be included in Appendix 3L (see Response to RAI 3.9-58).

DCD Impact

No DCD changes will be made in response to this RAI.

NRC RAI 3.9-63

The discussion provided in DCD Tier 2, Section 3.9.2.4 does not specifically address how the main steam lines in the ESBWR would be instrumented in order to identify the presence of acoustic resonances. Provide a discussion to demonstrate how the main steam lines in the ESBWR shall be instrumented to collect data to determine steam pressure fluctuations in order to identify the presence of acoustic resonances. Also discuss how the pressure fluctuations would be analyzed to determine steam dryer loading and stresses.

GE Response

The steam dryer instrumentation, main steam line instrumentation, and startup testing process is described in Subsection 3L.4.6 of DCD, Tier 2, Appendix 3L. Additional reference reports will be provided: General Electric Company, "Steam Dryer - Instrumentation and Power Ascension Monitoring," NEDC-33314P, Class III (Proprietary), and NEDO-33314, Class I (Non-Proprietary). See response to RAI 3.9-58.

DCD Impact

DCD Tier 2, Subsection 3L.4.6 and Section 3L.6 were revised as noted in the attached DCD Tier 2 Rev. 3 markup.

NRC RAI 3.9-64

The discussion provided in DCD Tier 2, Section 3.9.2.4 does not specifically address how the steam dryer data would be used to calibrate the main steam line instrumentation and data analysis prior to the removal or failure of the steam dryer instrumentation. Provide a discussion to address this concern.

GE Response

Calibration of the steamline acoustic monitoring model against the steam dryer instrumentation during startup testing is described in Subsection 3L.4.6 of DCD, Tier 2, Appendix 3L.

DCD Impact

DCD Tier 2, Subsection 3L.4.6 was revised as noted in the attached DCD Tier 2 Rev. 3 markup.

NRC RAI 3.9-66

The discussion provided in DCD Tier 2, Section 3.9.2.4 does not specifically state that the startup test procedure will include the stress limit curve to be applied for evaluating steam dryer performance. Verify that this curve would be included in the startup test procedure. Also provide the details of the stress limit curve which would be applied for the ESBWR steam dryer components.

GE Response

Development of the steam dryer instrumentation power ascension limits and monitoring during startup testing is described in Subsection 3L.4.6 of DCD Tier 2 Appendix 3L. Additional discussions of the vibratory stress limits are provided in Subsection 3L.5.5.2 of DCD Tier 2 Appendix 3L.

DCD Impact

DCD Tier 2 Subsections 3.9.2.3 and 3L.5.5.2 were revised as noted in the attached DCD Tier 2 Rev. 3 markup.

NRC RAI 3.9-71

The discussion provided in DCD Tier 2, Section 3.9.2.4 does not specifically state how the predicted and allowable amplitudes are obtained for the steam dryer components at significant locations. Provide a discussion to clearly explain how the predicted and allowable amplitudes are obtained for the steam dryer at all significant locations including the outer hood, skirt and all potential high stress areas.

GE Response

Development of the steam dryer instrumentation power ascension limits and monitoring during startup testing is described in Subsection 3L.4.6 of DCD, Tier 2, Appendix 3L.

DCD Impact

No DCD changes will be made in response to this RAI.

NRC RAI 3.9-133

It is not clear whether GE has committed to install instrumentation on the steam dryer in the prototype ESBWR plant for FIV response during power ascension. Although test and instrumentation plans are described in the report for some components, and GE lists the differences between the ESBWR and past BWR dryers in DCD Tier 2, Section 3L.5.5.1.3,stating that 'these differences warrant a detailed vibration analysis and test monitoring'; Item 5 in DCD Tier 2, Section 3L.2.1 (page 3L-4) implies that GE might submit a supplemental report asserting that 'FIV will not be an issue' for various components, which might include the steam dryer. Also, DCD Tier 2, Table 3L-4 lists many sensors that might be installed on the prototype steam dryer, and includes several caveats in the last column stating 'if problem occurs'. GE is requested to clarify the instrumentation that will be installed on the steam dryer, the main steam lines (MSLs), and steam system components, in the ESBWR prototype plant for FIV response during the startup power ascension. Also, GE is requested to clarify whether data for all equipment listed in DCD Tier 2,Table 3L-4 will be acquired during testing.

GE Response

As discussed in DCD Tier 2, Subsection 3L.2.1, all reactor internals were evaluated for susceptibility to flow induced vibration. The initial screening and evaluation of the reactor internals identified the chimney partition assembly and steam dryer for instrumentation and inclusion in the FIV test program. The prototype ESBWR steam dryer will be instrumented as described in DCD Tier 2, Subsection 3.9.2.4 (will be revised to include steam dryer as stated in RAI 3.9-61 response) and Subsection 3L.4.6 of DCD, Tier 2, Appendix 3L. The prototype ESBWR chimney partitions will be instrumented as described in Section 3L.5 of DCD, Tier 2, Appendix 3L. The initial screening eliminated the Control Rod Guide Tubes (CRGTs), In-Core Monitor Guide Tubes (ICMGTs), and In-Core Monitor Housings (ICMHs) from the FIV test program. The basis for eliminating these components is provided in DCD Tier 2, Subsection 3L.2.1.

More quantitative FIV evaluations are ongoing for the remaining components identified by the initial screening: Chimney Head/Steam Separator assembly, Shroud/Chimney assembly, and the Standby Liquid Control (SLC) line. The components will be evaluated using the approach and criteria listed in Items 1 through 4 in DCD Tier 2, Subsection 3L.2.1. Item 5 in DCD Tier 2, Subsection 3L.2.1 states that the results of these evaluations will be documented in a supplemental report. Depending on the results of the evaluations, the component may be eliminated from the FIV test program, identified for instrumentation and inclusion in the FIV test program, or further evaluated as described in DCD Tier 2, Subsection 3L.2.2. Item 5 does not apply to the steam dryer or chimney partition assembly; these components were already identified for inclusion in the FIV test program.

Currently, data for all of the equipment listed in DCD Tier 2, Table 3L-4 will be acquired during initial startup and power ascension testing. This list may be augmented or revised based on the outcome of the ongoing FIV evaluations. The general phrase "to obtain forcing function data if problem occurs" used in DCD Tier 2, Table 3L-4 applies to the pressure transducers. The pressure data will be recorded during the testing. The measurements from these sensors 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 useful for determining the source of any excessive vibration amplitudes, if they are to occur during testing. Detailed evaluations of the pressure data will only be performed if the primary vibration measurements (i.e., strain gauge or accelerometer) indicate the need for further assessment. Evaluation of the steam dryer pressure sensor measurements is described in Subsection 3L.4.6 of DCD Tier 2 Appendix 3L.

DCD Impact

No DCD changes will be made in response to this RAI.

NRC RAI 3.9-135

GE is requested to describe in detail (1) the source of the load definition of the ESBWR steam dryer, (2) the validation of the methodology used in developing the load definition, (3) the stress analysis performed using the load definition, (4) the error and uncertainties associated with the each aspect of the analysis, (5) the application of the error and uncertainties in the stress analysis, (6) the stress analysis results and comparison to acceptance criteria, and (7) the plans to confirm the steam dryer load definition and stress analysis using actual steam dryer data during plant operation.

GE Response

The ESBWR steam dryer evaluations are discussed in Section 3L.4 of DCD Tier 2 Appendix 3L. Three additional references (3L-5, 3L-6 and 3L-7) were added in Section 3L.6 as part of RAI 3.9-58 response for additional information.

Detailed discussion of the source of the load definition and validation of the load definition methodology will be included in Reference 3L-5: General Electric Company, “Steam Dryer - Acoustic Load Definition,” NEDC-33312P, Class III (Proprietary), and NEDO-33312, Class I (Non-Proprietary).

The steam dryer stress analysis and comparison to acceptance criteria will be included in Reference 3L-6: General Electric Company, “Steam Dryer - Structural Evaluation,” NEDC-33313P, Class III (Proprietary), and NEDO-33313, Class I (Non-Proprietary).

Details regarding the confirmation of the steam dryer load definition and stress analysis during initial power ascension will be included in Reference 3L-7: General Electric Company, “Steam Dryer - Instrumentation and Power Ascension Monitoring,” NEDC-33314P, Class III (Proprietary), and NEDO-33314, Class I (Non-Proprietary).

Each of these references will also address the uncertainties associated with that aspect of the overall dryer evaluation. The summation of the individual uncertainties and application to the overall evaluation will also be addressed in Reference 3L-7.

DCD Impact

No DCD changes will be made in response to this RAI.

NRC RAI 3.9-136

GE describes its procedure for assessing the integrity of the ESBWR steam dryer in Section 3L.4 of DCD, Tier 2, Appendix 3L. The procedure for defining the fluctuating pressure loads acting on the steam dryer is described in Section 3L.4.4, and uses a 'Load Interpolation Algorithm' (LIA) to compute a fine discretization of pressure time histories over the steam dryer surfaces based on measurements made in GE's scale model test (SMT) facility in Sunol, CA. The LIA includes acoustic finite element models as part of its load estimating process.

(a) GE is requested to submit the LIA method for review (including the Acoustic Finite Element modeling (AFEM) procedures), along with any data measured in the SMT that substantiates the method. Also,the documentation of uncertainties and bias errors in the LIA and AFEM is requested.

(b) GE asserts that the BWR/3 configuration of the SMT facility has been benchmarked against plant data acquired from an instrumented dryer that confirms its capability to predict steam dryer acoustic load definitions. Per SRP Section 3.9.2, Draft Revision 3,April 1996, GE is requested to submit this benchmarking information, along with an assessment of the SMT uncertainties and bias errors. Particular emphasis should be placed on confirming that the SMT can be used to predict the frequency content of the forcing functions associated with acoustic flow tones (or singing) caused by flow over the branch lines for MSL safety and relief valves.

GE Response

The ESBWR steam dryer evaluations are discussed in Section 3L.4 of DCD, Tier 2, Appendix 3L. A more detailed discussion of the source of the load definition and validation of the load definition methodology will be provided in a future report: General Electric Company, "Steam Dryer - Acoustic Load Definition," NEDC-33312P, Class III (Proprietary), and NEDO-33312, Class I (Non-Proprietary).

DCD Impact

DCD Tier 2, Subsections 3L.4.4, 3L.4.6 and Section 3L.6 were revised as noted in the attached DCD Tier 2 Rev. 3 markup.

NRC RAI 3.9-137

In Section 3.L.4.6 of DCD, Tier 2, Appendix 3L, GE describes potential steam dryer FIV measurements, including determination of the steam dryer as-built modal parameters. Impact hammer testing will be used to determine the natural frequencies, mode shapes, and damping of the steam dryer components. The data will be used to verify portions of the steam dryer analytical models.

(a) GE is requested to discuss the planned impact hammer testing (e.g., will the testing be conducted outside the plant, or with the steam dryer installed in the plant, with the skirt partially immersed in water) for the purposes of determination of the steam dryer as-built modal parameters.

(b) Per SRP Section 3.9.2, Draft Revision 3, April 1996, GE is requested to discuss the determination of the damping of the ESBWR steam dryer, and how the damping will be applied to their stress analysis models of the steam dryer.

GE Response

(a) The objective of the steam dryer hammer 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, tie bars and the skirt. These results will be used to verify portions of the finite element model of the 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 modal 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, welding, and residual stresses that affect the assumed boundary conditions in the finite element model. The mode shapes and frequencies determined by the hammer test will be used to validate the finite element modal analysis and determine the uncertainty in the finite element model predictions of the modal response.

The impact hammer test will be performed inside the plant with the dryer inside the dryer/separator pool. The tests will be performed with the dryer resting on simulated dryer support blocks similar to the way the dryer will be seated inside the reactor vessel. The hammer test will be performed when the installation of the sensors for in-reactor vibration measurement is completed.

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

(b) The structural analysis of the steam dryer will assume a damping coefficient of 1% for the vibration analyses. Higher values of damping coefficients may be considered if substantiated by test measurements including the hammer test results for the prototype ESBWR steam dryer.

DCD Impact

DCD Tier 2, Subsection 3L.4.6 was revised as noted in the attached DCD Tier 2 Rev. 3 markup.

NRC RAI 3.9-138

In Table 3L-4 of DCD, Tier 2, Appendix 3L, GE lists sensors that may be mounted to the steam dryer, the reactor dome, and other structures.

Describe the specific instrumentation, including the number of sensors and locations, to measure pressure, strain, and acceleration of steam dryer components for the purpose of providing sufficient information to evaluate the performance of the ESBWR steam dryer and to assess its continued structural capability during plant operation. As part of this description, GE is requested to explain the instrumentation specifications, including the following:

(a) How many accelerometers will be mounted to the steam dryer support ring and in what direction(s) will they be oriented?

(b) How many accelerometers will be mounted to the steam dryer skirt,and how many in circumferential positions?

(c) In what orientation(s) will the strain gages on the steam dryer hood,steam dryer drain channels, and steam dryer skirt be mounted?How many strain gages will be mounted at the above locations?

(d) How many strain gages will be mounted to the shroud, in what orientation(s), and in how many circumferential positions?

(e) Clarify the meaning of 'steam dryer FIV instrument post' for the pressure transducer to be mounted in the Vessel Dome Region.

GE Response

Table 3L-4 of DCD, Tier 2, Appendix 3L provides the general locations for the FIV information. The final number, location, and orientation of the accelerometers and strain gauges will be available after the final structural evaluations are completed and the high stress locations have been determined. Details regarding the steam dryer instrumentation will be provided in a new LTR and included as Reference 3L-7 in Section 3L.6 (see response to RAI 3.9-58).

Two strain gages will be mounted on the shroud surface near the high stress points around the middle of the shroud where the stresses are expected to be the highest for the lower structural modes. The azimuth location will be determined after the completion of the final detailed structural analysis. These sensors will be augmented by the displacement sensors (LVDT) on the top guide for confirming the FIV adequacy of the shroud.

The "steam dryer FIV instrument post" is the support mast used to lead the FIV instrumentation cabling from the top of the steam dryer to the vessel head penetration. A pressure transducer is mounted on this post above the dryer in order to measure the pressure fluctuations in the vessel head region.

DCD Impact

No DCD changes will be made in response to this RAI. Additional references were added to DCD Tier 2 Section 3L.6 as part of response to RAI 3.9-58.

NRC RAI 3.9-139

In Section 3L.4 of DCD, Tier 2, Appendix 3L, GE explains how the steam dryer instrumentation (strain gages, accelerometers, and pressure transducers) will be monitored against established limits.

(a) GE is requested to explain the determination of those limits for each type of instrumentation, particularly for the pressure transducers.

(b) Per SRP Section 3.9.2, Draft Revision 3, April 1996, GE is requested to list the corrective actions to be taken if the limit curves are exceeded, and the steam dryer stresses are deemed not acceptable for higher plant power operation.

GE Response

(a) The methodology for developing the strain gauge and accelerometer response acceptance criteria are described in Subsection 3L.5.2.2 of DCD, Tier 2, Appendix 3L. The acceptance criteria will be based on the steam dryer structural analysis results. The acceptance criteria for the pressure sensor data are based on the frequency and amplitude content of the design load definition used in the structural analysis.

(b) The acceptability of the dryer for continued operation will be 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. If necessary, more detailed structural analyses of the high stress regions of the dryer will be performed. After reanalyzing the dryer structure with the measured loading and refined modeling, if it is determined that the stresses are not acceptable for higher plant power operation, further power ascension will be delayed until such time that modifications to the dryer could be designed and installed.

DCD Impact

No DCD changes will be made in response to this RAI.

NRC RAI 3.9-141

In GE Report MFN 06-012 (NEDE-33259P), GE describes testing of the prototype ABWR plant in Japan, and provides a table of selected FIV parameters measured in the ABWR and estimated for the ESBWR. However, GE did not include steam dryer data in the table. To justify GE's classification of the ESBWR dryer as a Category II Non-Prototype (per Regulatory Guide 1.20, Revision 2, May 1981), GE is requested to provide ABWR or other valid prototype steam dryer FIV data relevant to the ESBWR design criteria, such as the presence of any strong tones in ABWR or other valid prototype, and ESBWR steam dryer FIV response. the fluctuating pressure loads incident on the steam dryer surfaces. Also, GE is requested to estimate any differences between the ABWR or other valid prototype, and ESBWR steam dryer FIV response.

GE Response

The prototype for the ESBWR steam dryer is the replacement dryer recently tested and installed in several BWR/3 plants that 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 SRV standpipes. The replacement dryer was specifically designed to withstand the flow-induced vibration and acoustic resonance loading that led to fatigue failures in the dryers for these plants. As described in Subsection 3L.4.4 of DCD Tier 2, Appendix 3L, the ESBWR SRV standpipe design is intended to reduce or eliminate acoustic resonances in these branch lines, thus reducing or eliminating this load on the dryer. Table 3L-1 provides a comparison between major configuration parameters of the ESBWR and the prototype replacement steam dryer.

DCD Impact

DCD Tier 2, Subsection 3L.4.1 and Table 3L-1 were revised as noted in the attached DCD Tier 2 Rev. 3 markup.

NRC RAI 3.9-146

Table 3.9-3 of ESBWR Design Control Document, Tier 2, provides 11.2 kPaD (kilopascal differential) as the maximum pressure difference for the steam dryer. However, there is likely to be a significant pressure variation across the outer hood of the steam dryer. GE is requested to describe the capability of the TRACG computer code to calculate such spatial pressure variation.

GE Response

The TRACG code is not used to calculate the spatial pressure variation across the outer hood. Computational fluid dynamics calculations for the prototype replacement steam dryer design show that the shape of the outer hood significantly reduces the spatial variation of the static differential pressure when compared to the earlier dryer designs and that the resulting spatial variation is fairly uniform.

DCD Impact

No DCD changes will be made in response to this RAI.

anchorage devices are designed in accordance with the requirements of the 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 envelop 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 the 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 flow-induced vibration 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. 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. This study provides useful predictive information for extrapolating the results from tests of components with similar designs to components of different 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 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 variable 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 plant are obtained from these correlation functions based on applicable values of the parameters for the prototype plant. 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 component stresses for each of the lower normal modes. The allowable amplitude in each mode is that which produces a peak stress amplitude of ±68.95 MPa (±10,000 psi). For the steam dryer and its components, a higher allowable peak 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 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.

RAI 3.9-66

Extensive predictive evaluations have been performed for the steam dryer loading and structural evaluation. These evaluations are described in Section 3L.4 of DCD Tier 2 Appendix 3L. The fatigue analysis performed for the ESBWR steam dryer will use a fatigue limit stress amplitude of 93.7 MPa (13,600 psi). For the outer hood component, which is subjected to higher pressure loading in the region of the main steam lines, the fatigue limit stress amplitude of 74.4 MPa (10,800 psi). The higher limit is justified because the dryer is a non-safety related component, performs no safety functions, and is only required to maintain its structural integrity (no loose parts generated) for normal, transient and accident conditions.

RAI 3.9-58

RAI 3.9-66

The dynamic loads caused by flow-induced vibration of the steam separators had 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 99,800 kg/hr (220,000 lbm/hr). Test results show a maximum flow induced vibration stress of less than 48.6 MPa (7200 psi), well below the GE acceptance criteria of 68.9MPa (10,000 psi). Thus it can be concluded that separator flow induced vibration effects are acceptable. Jet impingement from feedwater flow has no significant effect on the steam separator assembly since the separator skirt is above the feedwater flow impingement area.

3.9.2.4 Initial Startup Flow-Induced Vibration Testing of Reactor Internals

Reactor internals vibration measurement and inspection program is conducted only during initial startup testing. This meets the guidelines of Regulatory Guide 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.

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 include the following:

RAI 3.9-61

- Steam dryer, bending strain and accelerations;
- Chimney and partitions, lateral displacements and accelerations;
- Chimney head, lateral displacements and accelerations;
- SLC internal piping, bending strain, lateral.

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 control rod drive and incore housings. Access is provided to the reactor lower plenum for these inspections.

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

Regulatory Guide 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 Record, Appendix A to 10 CFR 50. This Regulatory Guide 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 Regulatory Guide 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 flow-induced vibrations 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 Regulatory Guide 1.20. GE is committed to confirm satisfactory vibration performance of 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. GE continues these test programs for the generic plants to verify structural integrity and to establish the margin of safety.

Refer to Subsection 3.9.9.1 for the information to be provided by the utility to the NRC on the reactor internals vibration testing program.

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 assumed break of main steam or feedwater line 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 a comprehensive vertical dynamic model of the RPV and internals. Besides the real masses of the RPV and core support structures, account is made for the water inside the RPV.

(2) External Pressure and Forces on the Reactor Vessel — An assumed break of the main steamline, the feedwater line or the RWCU/SDC line at the reactor vessel nozzle results in jet reaction and impingement forces on the vessel and asymmetrical pressurization of the annulus between the reactor vessel and the shield wall. These time-varying pressures are applied to the dynamic model of the reactor vessel system. Except for the nature and locations of the forcing functions, the dynamic model and the dynamic analysis method are identical to those for seismic analysis as described below. The resulting loads on the reactor internals, defined as LOCA loads, are considered as shown in Table 3.9-1.

(3) Safety/Relief Valve Loads (SRV Loads) — The discharge of the SRVs results in reactor building vibrations (RBV) due to suppression pool dynamics as described in Appendix 3B. The response of the reactor internals to the RBV is also determined with the dynamic model and dynamic analysis method described below for seismic analysis.

(4) LOCA Loads — The assumed LOCA also results in RBV due to suppression pool dynamics as described in Appendix 3B and the response of the reactor internals are again determined with the dynamic model and dynamic analysis method used for seismic analysis. Various types of LOCA loads are identified on Table 3.9-1.

(5) Seismic Loads — The theory, methods, and computer codes used for dynamic analysis of the reactor vessel, internals, attached piping and adjoining structures are described in Section 3.7 and Subsection 3.9.1.2. Dynamic analysis is performed by coupling the lumped-mass model of the reactor vessel and internals with the building model to determine the system natural frequencies and mode shapes. The relative displacement, acceleration, and load response is then determined by either the time-history method or the response-spectrum method. The loads on the reactor internals due to faulted event SSE are obtained from this analysis.

The above loads are considered in combination as defined in Table 3.9-2. The SRV, LOCA (SBL, IBL or LBL) and SSE loads as defined in Table 3.9-1 are all assumed to act in the same direction. The peak colinear responses of the reactor internals to each of these loads are added

3L.4 STEAM DRYER EVALUATION PROGRAM

3L.4.1 Steam Dryer Design and Performance

The ESBWR steam dryer will be designed using modules of dryer vanes enclosed in a housing to make up the steam dryer assembly. The modules or subassemblies of dryer vanes, called dryer units, will be arranged in six parallel rows called banks. The dryer banks will be attached to an upper support ring, which is supported by steam dryer support brackets that are welded attachments to the reactor pressure vessel (RPV). The steam dryer assembly will not physically connect to the shroud head and steam separator assembly and will have no direct connection with the core support or shroud. A cylindrical skirt will attach to the upper support ring and will project downward to form a water seal around the array of steam separators. Normal operating water level will be approximately mid-height on the dryer skirt.

Wet steam from the core will flow upward from the steam separators into an inlet header, horizontally through the dryer vanes, the outlet side perforated plates, vertically in the outlet header and out into the RPV dome. Dry steam will then exit the RPV through the steam outlet nozzles. Moisture (liquid) will be separated from the steam by the vane surface and the hooks attached to the vanes. The captured moisture will flow downward, under the force of gravity, to a collection trough that carries the liquid flow to vertical drain channels. The liquid will flow by gravity through the vertical drain channels to the lower end of the skirt where the flow will then exist below normal water level. The prototype for the ESBWR steam dryer is the replacement dryer recently tested and installed in several BWR/3 plants that 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 SRV standpipes. The replacement dryer was specifically designed to withstand the flow-induced vibration and acoustic resonance loading that led to fatigue failures in the dryers for these plants. Table 3L-1 provides a comparison between major configuration parameters of the ESBWR and the prototype replacement steam dryer.

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During normal refueling outages, the ESBWR steam dryer will be 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 will be installed and removed from the RPV by the reactor building overhead crane. A steam separator and dryer lifting device, which attaches to four steam dryer lifting rod eyes, will be used for lifting the dryer. Guide rods in the RPV will be used to aid dryer installation and removal. Upper and lower guides on the dryer assembly will be used to interface with the guide rods. The ESBWR steam dryer assembly is shown in Figure 3L-2.

3L.4.2 Materials and Fabrication

Current industry practice will be 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. New industry dryers are currently constructed from wrought 300 series stainless steel and Grade CF3 stainless steel castings. Except for the dryer vane material, the maximum carbon content of the wrought stainless steel will be limited to 0.02% and the maximum hardness of wrought 300 series stainless steel will be limited to Rockwell B92. Fabrication process controls are applied to minimize the degradation of material properties by forming, cold working, etc. Susceptibility to stress corrosion cracking will be avoided by careful control of the solution heat treatment, sensitization testing and testing for intergranular attack (IGA).

3L.4.3 Load Combinations

Design loads for the steam dryer will be based on evaluation of the ASME 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 dryer 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 Dryer

During normal operation, the dryer experiences a static differential pressure loading across the dryer plates resulting from the pressure drop of the steam flow across the vane banks. The dryer also experiences fluctuating pressure loads resulting from turbulent flow across the dryer and acoustic sources in the vessel and main steamlines. During transient and accident events, the dryer may also experience 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 pressure loads that act on the dryer during normal operation that has led to fatigue damage in previous dryer designs. Scale model testing has identified the likely sources of fluctuating pressure loading acting on the steam dryer. The results of this testing showed that the fluctuating pressure load frequency spectrum can be divided into four regions based on the postulated source of the loading:

- **0-10 Hz:** The pressure loads in this frequency range are dominated by the fundamental main steamline piping acoustics. The source of these pressure loads is believed to be turbulence in the main steamline or vortex shedding in steam dome.
- **10-30 Hz:** The source of the pressure loads in this frequency range is postulated to be a stationary vortex on the outer hood of the steam dryer adjacent to the vessel outlet nozzles. The frequency characteristics of this pressure loading may be governed by harmonics of the main steamline acoustics.
- **>30 Hz:** The lowest steam plenum acoustic modes are located in this frequency range. The dominant excitation is due to broadband turbulent sources located in main steamlines but the acoustic modes may also be excited by sources in the vessel. The plenum acoustic modes have a very high amplification effect on pressure oscillations in this frequency range. The lower frequency vessel acoustic modes exhibit the most significant response to the turbulent excitation present in the system. Higher frequency vessel acoustics exist but are not significantly excited except as discussed below.
- **120-200 Hz:** Strong narrow band pressure loads in this frequency range are caused by acoustic resonances in safety and relief valve branch lines attached to the main steamlines. Higher frequency steam plenum acoustic modes can be excited if the vessel is acoustically coupled to the branch line. The ESBWR SRV standpipe design is intended to reduce or eliminate acoustic resonances in these branch lines. It should be noted that the 120-200 Hz frequency range is approximate and is dependent on the SRV

standpipe design. The frequency range monitored in the FIV test program will be adjusted to bound the range of frequencies determined for the final design.

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A detailed description of the acoustic load definition process for the ESBWR steam dryer is provided in Reference 3L-5. The steam dryer acoustic load definition process consists of three primary elements:

- Scale model testing (physical testing using an ESBWR scale model to acquire load definition data, pressure and frequency, monitored by approximately 60 transducers),
- Acoustic finite element modeling of the reactor steam dome region to determine the natural frequencies and mode shapes of the steam volume, and
- A load interpolation algorithm to refine the measured fluctuating load into a fine mesh consistent with the structural finite element model nodalization in order to perform an accurate stress analysis of the dryer.

Flow induced turbulent and acoustic loads for the design of the ESBWR steam dryer will be determined from scale model testing of the dryer design and resultant acoustic modeling performed in the GE scale model testing facility located at the Vallecitos Nuclear Center in Sunol, California. The scale model test apparatus models the outside surface of the steam dryer above the vessel water level, the vessel steam dome region, and the main steamline piping to the turbine inlet, including major branch lines (e.g., SRV standpipes, turbine bypass piping). The testing is performed in ambient air conditions. Because the fluctuating pressure loads are primarily acoustic in nature, the test results are scaled to reactor conditions while preserving an equivalent Mach number between the model and the plant. GE has recently successfully completed a power ascension test program with an instrumented replacement BWR 3 steam dryer that is the prototype for the ESBWR steam dryer. The scale model test has been benchmarked against the plant data acquired from this instrumented dryer and confirms the capability of the GE scale model test methodology to predict the steam dryer acoustic load definitions.

The acoustic finite element modeling models the steam dryer and reactor steam dome cavity. This model is used to predict the acoustic mode shapes of the cavity and provides the framework for the load interpolation algorithm.

The load interpolation algorithm is used to provide a fine mesh load definition for input to the dynamic structural analysis. The algorithm uses the acoustic normal modes of the RPV steam plenum as a basis to describe the domain of interest. The algorithm uses the test measurements taken from the approximately 60 transducer locations on the scale model test and the acoustic finite element model to develop a fine-mesh array of pressure time histories that are consistent with the structural finite element model nodalization.

3L.4.5 Structural Evaluation

A finite element analysis (FEA) will be performed to confirm that the ESBWR steam dryer is structurally acceptable for operation. The FEA will use the scale model test loads as input. The finite element analysis will be performed using a whole dryer analysis model of the ESBWR steam dryer to determine the most highly stressed locations. The FEA consists of time history dynamic analyses for the load combinations identified in Table 3.9-2. If required, locations of high stress identified in the whole dryer analysis will be further evaluated using solid finite element models to more accurately predict stresses at these locations. The analysis will also confirm that the RPV dryer support lugs will accommodate the predicted dryer loads under normal operation and transient and accident conditions. (Also see 3.L.5.5.1.5.)

The structural evaluation of the ESBWR steam dryer design (Reference 3L-6) will be presented during the certification phase.

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3L.4.6 Instrumentation and Startup Testing

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The prototype ESBWR steam dryer will be 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 the actual pressure loading on the dryer during power operation is consistent with the pressure loading assumed in the structural fatigue evaluation and to verify that the new steam dryer can adequately withstand flow induced vibration forces for extended period as designed. The detailed objectives are as follows:

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

The objective of the steam dryer hammer 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, tie bars and the skirt. These results will be used to verify portions of the finite element model of the dryer.

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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 modal 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, welding, and residual stresses that affect the assumed boundary conditions in the finite element model. The mode shapes and frequencies determined by the hammer test will be used to validate the finite element modal analysis and determine the uncertainty in the finite element model predictions of the modal response.

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The impact hammer test will be performed inside the plant with the dryer inside the dryer/separator pool. The tests will be performed with dryer resting on simulated dryer support blocks similar to the way the dryer will be seated inside the reactor vessel. The hammer test will be performed when the installation of the sensors for in-reactor vibration measurement is completed.

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

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The steam dryer vibration sensors will consist of strain gauges, 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 will be based on past experience of similar tests conducted on other BWR steam dryers. These sensors will be specifically designed to withstand the reactor environment. Details of the steam dryer instrumentation are provided in Reference 3L-7.

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

Prior to initial plant start-up, strain gauges will be resistance spot-welded directly to the dryer surface. Accelerometers will be tack welded to pads that are permanently welded to the dryer surface. Surface mounted pressure sensors will be 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 will be welded to an annular pad that is welded permanently to the dryer surface. The sensor conduits will be routed along a mast on the top of the dryer and fed through the RPV instrument nozzle flange to bring the sensor leads out of the pressure boundary. Sensor leads will be 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 will be located in junction boxes inside the drywell. The data acquisition system will consist of strain gauges, pressure transducers and accelerometer signal conditioning electronics, a multi-channel data analyzer and a data recorder. The vibration data from all sensors will be recorded on magnetic or optical media for post processing and data archival. The strain gauges, accelerometer and pressure transducers will be field calibrated prior to data collection and analysis. The temporary vibration sensors will be removed after the first outage.

In addition to the instrumentation on the steam dryer, the main steamlines will be instrumented in order to measure the acoustic pressures in the steamlines. These pressure measurements will be used as input to an acoustic model for determining the pressures acting on the steam dryer. This

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acoustic model will be calibrated against the pressure transducer measurements taken on the steam dryer to provide an acoustic load definition for use in performing confirmatory structural evaluations. For non-prototype ESBWRs, the steamlines will be instrumented and the calibrated acoustic model will be used to confirm the pressure loads acting on the steam dryer. Details of the main steamline measurement instrumentation and acoustic model are provided in Reference 3L-7.

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During power ascension, the steam dryer instrumentation (strain gages, accelerometers and dynamic pressure transducers) will be monitored against established limits to assure the structural integrity of the dryer is maintained. If resonant frequencies are identified and increase above the predetermined criteria, power ascension will stop. The acceptability of the dryer for continued operation will be 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.

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Future steam dryer inspections will be in accordance with Reference 3L-2, and in accordance with Boiling Water Reactor Vessel Internals Program (BWRVIP) guidance.

- vertical displacement; and
- meridian rotation.

This shell model is applicable only to the axisymmetric finite element analysis of the shroud and vessel. Responses calculated from this model, other than that of the shroud, shall not be construed as being representative of other reactor components.

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

(1) Discrete components move in unison for guide tubes, steam separators, standpipes, and control rod drive housings 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 incore housings are neglected.

(4) Top guide beam and core plate are assumed to have zero rotational stiffness.

(5) Masses of CRD housings 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. Discrete components such as guide tubes are modeled as equivalent 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 1 vibration, n=1.

3L.5.5.1.3 Steam Dryer

The design of the steam dryer assembly for the ESBWR prototype plant is somewhat different from the original steam dryers used in previous BWR designs. Specifically, the major differences are in:

(1) the skirt and support ring diameters;

(2) the annulus size between the skirt and reactor pressure vessel;

(3) the flow path between the dryer banks and the vessel head; and

(4) the design details of the dryer skirt, drain channels and hoods.

In addition, the total steam flow rate of the ESBWR prototype 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 flow-induced vibration.

In the ESBWR prototype plant FIV test program of the dryer assembly, accelerometers and strain gages are located directly on the skirt, drain channels, support ring and hoods (Reference 3L-7). In addition, pressure sensors are used to measure the pressure differentials between the inside and outside of the dryer hood and dryer skirt. The differential pressure fluctuation across the dryer hoods is the primary forcing function causing vibration of the upper part of the dryer structure. The differential pressure fluctuation across the dryer skirt is the primary forcing function causing the vibration of the steam dryer skirt.

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A dynamic finite element model of the 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 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.

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The structural material properties and density for the dryer components at temperature are used in the model. The effect of the water on the dynamic responses is accounted for by using a direct lumped mass input. These added mass inputs include the submerged portions of the dryer skirt, drain channels, and the lower support ring.

Prior analytical models have predicted that the vibration modes are very closely spaced.

3L.5.5.1.4 Standby Liquid Control Lines

In the ESBWR prototype plant reactor, there are two standby liquid control pipes that enter the reactor vessel and are routed to the shroud. To accurately predict the vibration characteristic of the standby liquid control line, a dynamic finite element model of the entire line is developed using the ANSYS computer code. 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.

3L.5.5.2 Stress Evaluation

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. All three 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. Table 3L-7 lists the methods that are used for each instrumented component for the ESBWR prototype plant FIV test program. The acceptable fatigue limit stress amplitude for the reactor internals component material [68.9 MPa (10,000 psi)], with the exception of the steam dryer. The fatigue analysis performed for the ESBWR steam dryer will use a fatigue limit stress amplitude of [93.7 MPa (13,600 psi)]. For the outer hood component, which is subjected to higher pressure loading in the region of the main steam lines, the fatigue limit stress amplitude of [74.4 MPa (10,800 psi)]. The higher limit is justified because the dryer is a non-safety component, performs no safety functions, and is only required to maintain its structural integrity (no loose parts generated) for normal, transient and accident conditions.

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Method I is used for components that have many closely spaced vibration frequencies and/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 peak-to-peak (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 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.

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Method II is used for components that have many closely spaced vibration frequencies and/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.

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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 stress concentration factors 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 stress concentration factors 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.

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All three methods have identical initial steps to obtain mode shape factors for each natural mode. The first five steps for all three 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 and for LVDTs. The example assumes a maximum allowable stress amplitude for the material of [68.9 MPa (10,000 psi)] for the purposes of illustration):

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(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, stress concentration factors 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.

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

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., 1.862 x 105 MPa (27.0 x 106 psi) at 160°C]

This equation is for uniaxial stress components. A similar, but more complex procedure will be used for biaxial stress structures such as the dryer skirt, drain channel and hood.

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.

(6) 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 the modal analysis of the finite element model on the computer. The modes 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 any good text book on the subject of basic vibration analysis, such as Reference 3L-4.

(7) 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 any good vibration analysis textbook, such as Reference 3L-4.)

The next step is similar for both Methods I and II, the only difference being that Method I will include the entire frequency range into one group, while Method II will break into several frequency ranges.

(8) 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:

3L.6 REFERENCES

3L-1 General Electric Company, "ESBWR Reactor Internals Flow Induced Vibration Program – Part 1", NEDE-33259P, Class III (Proprietary), January 2006, and NEDO-33259, Class I (Non-proprietary), January 2006.

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

3L-3 *ANSYS Engineering Analysis System User's Manual*, G.J. DeSalvo and R.W. Gorman, Swanson Analysis Systems, Inc., Houston, PA, Revision 4.4a, May 1989.

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

3L-5 General Electric Company, "Steam Dryer - Acoustic Load Definition," NEDE-33312P, Class III (Proprietary), October 2007, and NEDO-33312, Class I (Non-Proprietary), October 2007.

3L-6 General Electric Company, "Steam Dryer - Structural Evaluation," NEDE-33313P, Class III (Proprietary), October 2007, and NEDO-33313, Class I (Non-Proprietary), October 2007.

3L-7 General Electric Company, "Steam Dryer - Instrumentation and Power Ascension Monitoring," NEDE-33314P, Class III (Proprietary), October 2007, and NEDO-33314, Class I (Non-Proprietary), October 2007.

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Table 3L-1

Comparison of Major Steam Dryer Configuration Parameters

Steam Dryer Configuration Parameter	ESBWR Dryer	Replacement BWR/3 Dryer
Number of Banks	6	6
Active height (flow area) for vane modules	1829 mm (65.6 m^2)	1829 mm (54.3 m^2)
Approximate weight	60,000 Kg	45,545 Kg
Outside diameter of upper support ring	6920 mm	6096 mm
Overall height	5700 mm	5436 mm
Length of skirt	2736 mm	2692 mm
Skirt thickness	9 mm	9.65 mm
Cover plate thickness	25.4 mm	25.4 mm
Hood thickness	25.4 mm (outer bank) 12.7 mm (inner banks)	25.4 mm (outer bank) 12.7 mm (inner banks)
Upper support ring cross-section	89 x 242 mm	152.4 x 203.2 mm
Average steamline flow velocity	49.7 m/s	61.6 m/s

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