**ENCLOSURE 15**

**TENNESSEE VALLEY AUTHORITY**
**BROWNS FERRY NUCLEAR PLANT (BFN)**
**UNIT 1**

**PROPOSED TECHNICAL SPECIFICATIONS (TS) CHANGE TS - 431 - REQUEST FOR LICENSE AMENDMENT FOR EXTENDED POWER UPRATE OPERATION**

**NON-PROPRIETARY VERSION OF THE GE ENGINEERING REPORT BROWNS FERRY NUCLEAR PLANT UNITS 1, 2, AND 3 STEAM DRYER ANALYSIS FOR EXTENDED POWER UPRATE**

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(See Attached)

**GE Nuclear Energy**

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## Engineering Report

# Browns Ferry Nuclear Plant Units 1, 2 and 3 Steam Dryer Analysis for Extended Power Uprate Conditions

Task T3005

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## IMPORTANT NOTICE REGARDING THE CONTENTS OF THIS REPORT

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## ACRONYMS AND ABBREVIATIONS

| Item | Short Form | Description |
|---|---|---|
| 1 | ASME | American Society of Mechanical Engineers |
| 2 | BFNP | Browns Ferry Nuclear Plant |
| 3 | BWR | Boiling Water Reactor |
| 4 | CFD | Computational Fluid Dynamics |
| 5 | SCF | Stress Concentration Factor |
| 6 | DS | Dynamic Stress |
| 7 | DLF | Dynamic Load Factor |
| 8 | EPU | Extended Power Uprate |
| 9 | EPU Value | Value corresponding to evaluation at EPU conditions |
| 10 | FEA | Finite Element Analysis |
| 11 | FEM | Finite Element Model |
| 12 | FIV | Flow Induced Vibration |
| 13 | ft/sec | Feet per second |
| 14 | GE | General Electric |
| 15 | GENE | General Electric Nuclear Energy |
| 16 | Hz | Hertz |
| 17 | IGSCC | Intergranular Stress Corrosion Cracking |
| 18 | MS | Main Steam |
| 19 | MSIV | Main Steam Isolation Valve |
| 20 | MSL | Main Steam Line |
| 21 | Mlbm/hr | Millions pounds mass per hour |
| 22 | $MW_{th}$ | Megawatt Thermal |
| 23 | NA | Not Applicable |
| 24 | NC | Not Calculated |
| 25 | NRC | Nuclear Regulatory Commission |
| 26 | OBE | Operational Basis Earthquake |
| 27 | OLTP | Original Licensed Thermal Power |
| 28 | OLTP Value | Value corresponding to evaluation at OLTP conditions |
| 29 | PS | Plant-Specific |
| 30 | Pb | Primary Bending Stress |
| 31 | Pm | Primary Membrane Stress |
| 32 | psi | Pounds per square inch |
| 33 | Re | Reynolds Number |
| 34 | RIPD | Reactor Internal Pressure Difference |

| Item | Short Form | Description |
|---|---|---|
| 35 | Ref | Reference Plant |
| 36 | Ref. | Reference |
| 37 | rms | root-mean-squared |
| 38 | RPV | Reactor Pressure Vessel |
| 39 | S | Strouhal Number |
| 40 | SF | Scaling Factor |
| 41 | SIL | Services Information Letter |
| 42 | SLO | Single Loop Operation |
| 43 | SRSS | Square Root Sum of Squares |
| 44 | SRV | Safety Relief Valve |
| 45 | SST | Stainless Steel |
| 46 | 0-P | Zero-to-Peak |

# 1. EXECUTIVE SUMMARY

Finite element analyses were performed using a whole dryer analysis model of the Tennessee Valley Authority, Browns Ferry Nuclear Plant (BFNP) Units 1, 2, and 3, BWR/4 steam dryer to determine the most highly stressed locations associated with operation at Extended Power Uprate (EPU) conditions. The analyses consisted of frequency calculations, equivalent static analyses, and a confirmatory dynamic response spectrum evaluation. In addition, ASME-based load cases were also applied to the finite element model. Chosen for the analysis was a steam flow rate of 13.372 Mlb/hr for the Original License Thermal Power (OLTP) level and 16.440 Mlb/hr for the EPU Operating level. An OLTP value of 3293 MWth and an EPU value of 3952 MWth were chosen for the analysis in order to bound all three Units.

The process had several steps that are explained in more detail throughout the report. The first step required the development of a complete 3-dimensional (3-D) finite element model of the BFNP steam dryer. Concurrent with constructing the model, efforts were undertaken to develop specific fluctuating loads for the Unit 1 steam dryer again with the intention to bound all three BNFP Units with a single analysis. Fluctuating loads were then calculated using a GENE-developed scaling methodology derived from actual pressure and strain gauge data taken from instrumented BWR steam dryers.

Using the 3-D finite element model, BFNP specific natural frequencies were determined for all of the outer surface dryer components. The model was then subjected to the specific pressure loads for both OLTP and EPU conditions. The static load analysis results identified peak stress locations in different individual steam dryer components based on the BFNP EPU steam velocities. Based on these analysis results, Flow Induced Vibration (FIV) peak stresses were determined for all of the dryer components including the outer cover plate, outer hood slanted plates, the hood top plate, the outer hood end plates and the outer hood stiffeners.

The analysis predicted that the majority of the steam dryer components are not vulnerable to fatigue at the EPU conditions. For the 3/8-inch thick outer cover plate, however, the ¼-inch fillet weld that joins the cover plate to the outer hood is predicted to experience fluctuating loads at EPU conditions that could lead to fatigue initiation. The criterion used in the evaluation to predict failure of the individual components was an ASME fatigue limit peak stress greater than 13,600 psi. The results of the evaluation based on the ASME criteria led GENE to recommend that modifications be made in order to lower the peak stress levels for the outer cover plate. and outer hood stiffeners prior to EPU. The outer hood and inner hood stiffener locations are also regions of higher stress at EPU conditions. Therefore, it is recommended that actions be taken to further evaluate the fluctuating stresses prior to extending power to a 120% EPU. Mitigation recommendations to address these locations are presented, and the report also discusses existing indications.

## 2. INTRODUCTION AND BACKGROUND

### 2.1 QC 1 and QC2 Events

In March of 2002, Quad Cities Unit 2, operated by Exelon, reached an uprated power level of 117% OLTP after its planned refueling outage and began continuous operation at this power level. On June 7, 2002, several anomalous readings related to pressure, water level, steam flow and moisture carryover were detected. Initial evaluation by GE concluded that the BWR/3 steam dryer was operating in a degraded condition. After 34 days of continuous monitoring of Quad Cities Unit 2, the Unit was shutdown July 11$^{th}$, 2002 to perform visual inspection of the steam dryer. The inspection revealed one cover plate adjacent to one of the outer bank inlet hoods was missing.

The root cause was identified at that time as high cycle fatigue caused by high frequency pressure loading. The result of the root cause evaluation showed that the catalyst for this event was a flow instability that resulted in localized, high cycle high-pressure loadings near the main steam line (MSL) nozzles. The high vibratory stresses from the pressure loading eventually resulted in the high cycle fatigue failure of the cover plate. Quad Cities, Unit 2 replaced both damaged and undamaged ¼-inch cover plates with new ½-inch cover plates and ½ inch fillet welds and the Unit was returned to its extended power uprate (EPU) operating level of 117% OLTP. The thicker ½-inch cover plate was able to withstand both the turbulent and resonant stresses.

On April 16, 2003, Quad Cities Unit 2 while operating at 117% OLTP, experienced an inadvertent opening of a pilot operated relief valve (PORV). The unit was shut down and the PORV replaced. On May 2, 2003, following return to EPU conditions, a greater than four-fold increase in the moisture content was measured. On May 28, 2003, the power level was reduced to pre-EPU conditions. A detailed statistical evaluation of key plant parameters concluded that a subtle change in the MSL flows had occurred following the April 16, 2003 PORV event. Based on this information, concurrent with the moisture content increase, the utility elected to shut down the unit on June 10, 2003 and perform a steam dryer inspection.

Detailed inspection of the steam dryer during the outage revealed significant damage. On the side closest to the PORV that had opened, a through-wall crack approximately 90 inches long and up to three inches wide was observed in the top of the outer hood cover plate and the top of the vertical hood plate. Three internal braces in the outer hood were detached and one internal brace in the outer hood was severed. On the opposite side of the steam dryer, incipient cracking was observed on the inside of the outer cover plate and one vertical brace in the outer hood was cracked. No damage was found in the cover plates that had been replaced following the first steam dryer failure in 2002. Three tie bars on top of the steam dryer were also cracked. (Note: tie bar cracking which has occurred in many plants at OLTP is believed to be unrelated to the other damage).

After extensive metallurgical and analytical evaluations, the dominant cause identified in the second steam dryer failure was high cycle fatigue due to low frequency pressure loading. Low frequency pressure loading may have also been a contributing factor in the first failure. Following the second failure, steam dryer modifications included replacing damaged ½ inch outer hood plates with 1 inch plates, removing internal brackets that attached the internal braces to the outer hood, adding gussets at the outer vertical hood plate and cover plate junction and adding stiffeners to the vertical welds and horizontal welds on the outer hood. The combined effect of these modifications was to increase the natural frequency of the outer hood and reduce the maximum stress by at least a factor of two, thereby reducing the response to the pressure loading in the steam flow near the MSLs. .Following the steam dryer modifications, the unit was returned to service on June 29, 2003.

On October 26, 2003, Quad Cities Unit 1 exhibited a subtle change in the MSL flow distribution. On October 31, 2003, the steam moisture content began trending upward. Based on this information, concurrent with the moisture content increase, the utility elected to shut down the unit on November 12, 2003 and perform a steam dryer inspection. Detailed inspection of the steam dryer during the outage revealed significant damage to the outer hood similar to that observed on Unit 2 in June 2003. A portion of the outer vertical hood plate came free and became a loose part in the reactor vessel. In addition, cracking was observed at the lower end of two of the diagonal braces on the inner hoods. The root cause of the outer hood failure was determined to be high cycle fatigue due to low frequency pressure loading; the same as that for the Unit 2 failure in June 2003. The root causes for the inner hood diagonal brace failure were determined to be the configuration of the brace attachment, which was unique to Unit 1, and the quality of the welds in the attachment. The Unit 2 hood plate and gusset modifications were applied to the Unit 1 dryer and the diagonal braces were removed from the inner banks. Following the steam dryer modifications, the unit was returned to service in November 2003.

During the Quad Cities 2 dryer inspection during the Spring 2004 refueling outage, cracking was observed in some of the previous repairs and modifications. The welds at the tips of three of the six front hood gussets added during the 2003 modifications were cracked, one of the tie bars bridging the outer bank weld was cracked, and the welds on some of the perforated plate insert brackets were cracked. It was determined that the repair configurations implemented in 2003 were not always consistent with the analyzed configurations. The analyses and repair design did not adequately address the uncertainty in the loads acting on the dryer; in particular, there was insufficient margin to accommodate the local stress concentrations in the repair configurations that could lead to fatigue damage. The cause of the cracking observed in the perforated plate insert brackets is believed to be the same relative displacement between dryer banks that leads to tie bar cracking. The entire vertical hood plate and outer gussets were replaced with a configuration that reduced the stiffness at the tip of the gusset. The outer tie bars were replaced. The perforated plate insert brackets were used "as is" because these components are not required for the overall structural integrity of the dryer and the intact welds were considered sufficient to hold the inserts in place for the next cycle. Following the steam dryer modifications, the unit was returned to service at the completion of the refueling outage.

Steam dryers at all three BFNP Units are a BWR/4 style with a slanted front hood. The slanted front hood and other design changes represents a significant improvement in susceptibility to fatigue cracking caused by flow induced vibration over the BWR/3 square hood style steam dryer found at Quad Cities. The principal design change leading to this improvement is the replacement of the inner diagonal braces with the internal vertical hood stiffeners. The stiffeners removed the high stress concentration where the cracks initiated in the Quad Cities failures and also provide support to the outer vertical hood panels that receive the highest fluctuating loads. A second difference between BFNP and Quad Cities plants is that BFNP has lower steam flow velocities at BFNP for both OLTP and EPU conditions as compared to those conditions in Quad Cities. The fluctuating pressure loads that led to the failures at Quad Cities are believed to be caused by acoustic sources in the main steamlines. The amplitude of the fluctuating pressure loads is a strong function of the steam flow velocity in the steamlines. The Quad Cites steam dryers experience an average steam flow velocities of 168 ft/sec at OLTP and 202 ft/sec at EPU compared with average velocities of 128 ft/sec at OLTP and 157 ft/sec at EPU for the BFNP Units. Therefore, the fluctuating pressure loads acting on the BFNP steam dryers are expected to be significantly lower than those at Quad Cities.

## 2.2 SIL 644, Supplement 1

In August of 2002, GE issued SIL 644 to provide information to all BWR utilities on cover plate related failures. In September of 2003, GE added Supplement 1 to SIL No. 644 in order to describe the second steam dryer failure, and to explain that the root cause of the second failure, which was different than the first failure. SIL 644 applied to BWR/3-style steam dryer design plants. Supplement 1 to SIL No. 644 provides recommendations applicable to plants like BFNP with BWR/4 and later design steam dryers.

Supplement 1 to SIL No. 644 states that no significant steam dryer damage is expected for BWR/4 and later steam dryer designs, at normal or EPU conditions. This conclusion is based on the assumption that there are no pre-existing flaws or undersized welds in the cover plates and outer hood locations. The SIL still had several recommendations for BWR/4 plants. These are as follows:

"Implement the following BWR/3 recommendations:

- Review available visual inspection records to determine if there are any pre-existing flaws or undersized welds in the cover plate and outer hood locations.

- Measure moisture content, as determined by Na-24 measurements in the reactor water and condenser hotwell, to establish a baseline value for operation near maximum core thermal power operating conditions. Measure and record the moisture content to a resolution of 0.1% or smaller. Isolate (or account for) flow through paths where reactor water can flow directly to the hotwell (e.g., reactor water cleanup reject flow, sample lines). Establish reactor pressure, water level, steam flow, and feedwater flow values consistent with the baseline moisture content values. Moisture content can change during the operating cycle due to changes in core power, core flow, or core radial peaking.

- Monitor reactor pressure, water level, individual steamline flow, and feedwater flow on a daily basis for significant anomalies (such as step changes in indicated values) that may indicate a steam dryer failure. Monitor and compare indications on each instrument reference leg; a dryer failure near the reference leg tap may affect the indications for the sensors on that reference leg. The step changes that were observed during the 2002 cover plate failure were usually small (2-3 psi for reactor pressure, ~two inches for reactor level,

~5% for steamline flow); therefore, trend plots of the data will be useful for performing the recommended monitoring.

- Implement a moisture content monitoring program that measures moisture content at least once every two (2) weeks when operating above the OLTP. If a significant change or a steadily increasing trend is observed, evaluate recent plant maneuvers or events and associated plant parameters to identify the cause of the increased moisture content. If the cause of the increased moisture content cannot be determined, consider a reduction in power or an orderly plant shutdown for inspection. The moisture content action level for initiating the increased monitoring and evaluations must be determined from the observed baseline values and normal variations. For example, an observed moisture carryover of 0.2% would be a significant change for an efficient dryer (normal moisture carryover of ~0.05%). For a plant that operates with high moisture levels, an observed moisture carryover 0.1% higher than the normal range would be significant. Following a transient event that may result in pressure loading of the steam dryer (relief valve opening, turbine stop valve closure, etc.), monitor moisture content daily until the structural integrity of the dryer is confirmed. Once it has been established that the dryer has sustained no damage, routine monitoring may be resumed. However, the moisture content monitoring frequency can be relaxed to once per month."

"Implement the following BWR/4 and later steam dryer design recommendations:

- Perform a visual inspection ("best effort" VT-1) prior to initial operation above the OLTP or within the next two scheduled refueling outages if already operating above the OLTP. This inspection should include the most susceptible locations as determined by a dryer stress analysis including the vertical rib areas on each of the outer hoods and the end plates on the two outermost banks. This inspection can be limited to an external inspection of the most susceptible locations.

- Repeat the visual inspections at every other refueling outage."

These recommendations are applicable to all BWR/4s and stand as the baseline inspection approach for assuring steam dryer integrity until industry Inspection and Evaluation Guidelines are in place.

SIL 644 Supplement 1 is currently being revised in order to present the recent dryer failure experiences at Quad Cities Units 1 and 2. The revision will also provide additional guidance with respect to monitoring plant parameters (e.g., steam moisture content, individual steamline flows) to aid in the detection of potential structural failures of the dryer during operation.

## 2.3 Dryer Design Bases and Historical Development

The function of the steam dryer is to remove liquid that is left in the steam exiting from the array of axial flow steam separators. GE BWR steam dryers use commercially available modules of dryer vanes that are enclosed in a GE designed housing to make up the steam dryer assembly. The modules or subassemblies of dryer vanes, called dryer units, are arranged in parallel rows called banks. Four to six banks are used depending on the vessel size. Dryer banks are attached to an upper support ring, which is supported by four to six steam dryer support brackets that are welded attachments to the RPV. The steam dryer assembly does not physically connect to the shroud head and steam separator assembly and it has no direct connection with the core support or shroud. A cylindrical skirt attaches to the upper support ring and projects downward forming a water seal around the array of steam separators. Normal operating water level is approximately mid-height on the dryer skirt. During refueling the steam dryer is supported from the floor of the equipment pool by the lower support ring located at the bottom edge of the skirt. Dryers are installed and removed from the RPV by the reactor-building crane. A steam separator and dryer strongback, which attaches to four steam dryer lifting rod eyes, is used for lifting the dryer. Guide rods in the RPV are used to aid dryer installation and removal. BWR steam dryers typically have upper and lower guides that interface with the guide rods.

Wet steam flows upward from the steam separators into an inlet header, horizontally through the perforated plates and dryer vanes, vertically in an outlet header and into the RPV dome. Steam then exits the reactor pressure vessel (RPV) through 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 drain pipes and vertical drain channels. The liquid flows by gravity through the vertical drain channels to the lower end of the skirt where the flow exits below normal water level.

GE BWR steam dryer technology evolved over many years and several product lines. In earlier BWR/2 and BWR/3 dryers, the active height of the dryer vanes was set at 48 inches. In BWR/4/5 steam dryers the active vane height was increased to 72 inches. Perforated plates were included on the inlet and outlet sides of the vanes of 72-inch height units in order to more effectively utilize the increased vane height. The addition of perforated plates resulted in a more uniform velocity over the height of the vanes. The BWR/4/5 dryer performance was established by testing in steam.

All of the BWR/2-6 steam dryers are welded assemblies constructed from type 304 stainless steel. The type 304 stainless steel used in BWR/2-6 steam dryers was generally purchased with a maximum carbon content specification of 0.08% (typical ASTM standard). Therefore, the weld heat affected zone material is likely to be sensitized during the fabrication process. Temporary welded attachments may have also been made to the dryer material that can result in unexpected weld sensitized material. Steam dryer parts such as support rings and drain channels were frequently cold formed, also increasing susceptibility. Many dryer assembly welds included crevice areas at the weld root, which were not sealed from the reactor environment. Cold formed 304 stainless steel dryer parts were generally not solution annealed after forming and welding. Therefore, steam dryers are prone to intergranular stress corrosion cracking (IGSCC).

Most of the steam dryer is located in the steam space but the lower half of the skirt is below normal water level. These environments are highly oxidizing. Average steam flow velocities through the dryer vanes at OLTP conditions are relatively modest (2 to 4 feet per second). However, local regions, near the steam outlet nozzles are continuously exposed to steam flows in excess of 100 feet per second. Thus, there is concern for flow-induced vibration (FIV).

The primary design basis for the dryer, a non-safety related component, is to maintain overall structural integrity and not generate loose parts that may interfere with main steam isolation valve closure during a steam line break accident. This faulted environment includes higher than normal two-phase flow through the dryer as well as bypass flow through the annulus between the dryer skirt and the inside of the RPV.

## 2.4 Motivation for Additional FIV and Structural Analysis

SIL 644, Supplement 1 indicated that the steam dryer should be inspected at the high stress locations. The experiences at Quad Cities and the root cause evaluation clearly established the role of steam velocity on the steam flow induced fluctuating loading of the dryer. This provided the motivation for quantifying the stresses in the BFNP steam dryer at both the OLTP and EPU conditions. The results of such evaluations also provide the technical basis for performing the GE recommended steam dryer modifications prior to operation at EPU conditions.

This evaluation was initiated to perform a quantitative assessment of the BFNP steam dryer. The GE load definition was used as input to a three-dimensional finite element model of the BFNP steam dryer. Loads considered in the assessment included steady state pressure, fluctuating, and transient loads, with the primary interest in the steady state fluctuating loads. Additionally, ASME-based design load combinations were evaluated for normal, upset and faulted service conditions. A detailed finite element analysis using the dryer model subjected to these design loads was also performed. The analytical results identified the peak stresses and their locations. The results of the analysis also included the analytically determined structural natural frequencies for the different key components/locations in the dryer.

A comparison of the predicted stresses with allowable steam dryer component stresses was used to identify locations that would be susceptible to fatigue and could affect plant operation at EPU conditions. For this evaluation, the report then identifies vulnerabilities of the steam dryer for BFNP at EPU conditions and makes recommendations based on lessons learned from the Quad Cities Unit 2 cover plate and outer hood failure events.

## 3. PROCESS OVERVIEW

The evaluation process for the steam dryer has several parts. The primary objective is to determine the locations of vulnerability to flow induced vibration. The dryer is a complex structure that varies in design from plant to plant. Thus, analysis required the development of a 3-D finite element structural model (FEM) based on the actual BFNP steam dryer drawings. This model is the basis of assessing the imposed stresses attributable to the steady state and fluctuating loads that have been measured on instrumented dryers and which were the root cause for the Quad Cities Unit Steam Dryer fatigue failure.

To calculate the fluctuating portion of the applied loads, measured plant data was used to develop a BFNP specific pressure spectrum. This spectrum was then used to assess the magnitude of the peak stresses for the outer hood and cover plate locations. The process also employed 3-D computational fluid dynamic (CFD) modeling of the flow in the steam dome to evaluate the spatial distribution and magnitudes of the steady state steam flow induced loads on the dryer components. Concurrently, the standard design loads for the BFNP steam dryer were defined to assess the steam dryer's design stresses against standard ASME criteria. Although the steam dryer was not built to ASME Code, these evaluations provide an understanding of the predicted stresses as compared to the code in case an upset event was to occur.

Using the different loads as inputs, the FEM was used to assess the vulnerabilities of the steam dryer. An "equivalent static" process was used to assess the relative fluctuating stresses for both the OLTP and the EPU conditions. A response spectrum method was then used to confirm the results of the equivalent static method. All of the analyses were used in developing the modification recommendations before ascension to EPU conditions. Each of the following sections provides additional details of the steps followed and the results of the analyses.

Only slight differences exist between the BFNP Unit 1 and Unit 2/3 steam dryers (e.g. hold down bracket location). The support ring is a much stiffer structure than the upper dryer structure (the region of concern in this analysis); therefore, the overall analysis is not sensitive to minor differences in the hold down bracket location. Therefore, a single BFNP model that is representative of all three Units was created and used for the evaluations reported herein.

## 4. WHOLE DRYER ANALYSIS

The primary objective of the 3-dimensional whole steam dryer analyses was to identify the relative sensitivity of the different dryer components to the fatigue. The fatigue compliance presented in Table 7-1 is evaluated based on the dryer response to the fluctuating component of the FIV load. In addition, the dryer components were evaluated for the different load combinations provided in Table 5-1. The following outlines the scope of the structural analysis:

Dryer natural frequencies and stresses were calculated using the ANSYS finite element code (Version 6.1 running under the Windows 2000 operating system). The dryer structure is dynamically isolated from the dryer skirt by the support ring. This is a result of the stiff support ring structure, cross bracing from the dryer support plates, and bottom beams. Therefore, the analyses were limited to the steam dryer excluding the lower skirt.

The lower skirt region has a history of minor indications in several plants at both original and uprate power levels. Cracks have occurred in the drain channel attachment welds and in the skirt near the drain channels and guide channels. Both IGSCC and high cycle fatigue have been identified as failure mechanisms for these cracks; the cause depends on the circumstances for the individual failure. These failures have been discussed in SIL 474. Because the lower skirt is partially submerged in the water, the skirt is subject to both the FIV fluctuating pressure loads that act on the upper components of the dryer and hydrodynamic loads from the liquid flow spillover from the steam separators. The fluctuating pressure loads on the skirt will be somewhat attenuated at both OLTP and EPU conditions by the narrow annular gap between the skirt and the vessel wall and are lower than the pressure loads on the upper components of the steam dryer. The fluctuating pressure loads on the skirt will increase at EPU conditions. There will be no increase in core flow rate with EPU. At the higher EPU power levels, the liquid spillover flow will be less. In addition, the water level inside the skirt will be lower at EPU power levels. It is expected that both of these effects will result in a reduction in the hydrodynamic loads on the skirt. The overall effect of these changes is that the loading on the lower skirt region will not be significantly affected by EPU. Therefore, a detailed structural analysis of the lower skirt was not performed for this evaluation.

The finite element analysis model of the steam dryer above the dryer skirt is shown in Figures 4-1 through 4-6. The model includes the dryer support ring with the base-plates, drain troughs, dryer hoods, and the steam dam above the dryer with its support gussets, all modeled with shell elements. The dryer vane bundles and perforated inserts are modeled as plates with sufficient stiffness so as not to interact with lower vibration modes of the steam dryer structure. The tie bars are modeled as beam elements.

Components, with the exception of the dryer vanes and the support ring, were modeled to represent their masses based on as-drawn dimensions and a material density of 0.29 lb/in$^3$. Density of the plates representing the dryer vanes was adjusted to represent the weight of the dryer vanes. Density and stiffness of the dryer support ring was adjusted to include the weight and stiffness of the dryer skirt. Figure 4-7 provides an overview of the major components evaluated.

# 5. LOAD DEFINITION

Section 5.1 describes the development and application of the fluctuating pressure load on the outer surfaces of the dryer. Section 5.2 describes the load combinations used in the BFNP dryer screening analysis.

## 5.1 Fluctuating Load Definition

The evaluation of the steam dryer's susceptibility to FIV is strongly tied to the assumptions regarding the fluctuating loads that the dryer experiences under normal operation. The evaluations for the Quad Cities Unit 2 steam dryer identified that the fluctuating loads are directly related to the acoustic characteristics of the reactor dome/steam line/relief valve configurations. The best source of data to assess the fluctuating loads can be derived from previous measurements on instrumented dryers. The available information was used in this manner. First, the reference load definition for the static scaling process was developed using all the available in-plant pressure measurements from instrumented steam dryers. The reference load definition used detailed pressure versus frequency spectrums based on in-plant measurement data for one domestic GE BWR and two foreign GE BWRs. The measured spectrum for each sensor was adjusted for sensor location to determine an effective pressure at the dryer hood vertical face. The maximum sensor readings were plotted together to form a single overall spectrum. The spectrum was then divided into frequency zones based on the general characteristics and peaks within the zone. Observations from two additional domestic GE BWRs and one foreign GE BWR were used to further define the frequency zones. The magnitude of the reference load was set equal to the peak value within each zone. For plant-specific applications, scaling factors were determined for each frequency zone based on the plant steamline flow velocity compared to the reference plant steamline flow velocity. [[

]].

### 5.1.1 *Reference Load Definition*

GE laboratory scale model test measurements were used to develop multipliers to adjust the plant signal readings from the plant measurement location (e.g., skirt, mast) to arrive at an effective pressure at the dryer vertical face. [[

]].

The maximum of the sensor readings as a function of plant power level was found at each frequency for each plant sensor. The maximum reading was then multiplied by the appropriate multiplier ([[ ]]) to determine the equivalent vertical face pressure (Figure 5-1).

The adjusted maximums for each sensor were then plotted together on one plot. An envelope was drawn based on the maximum of all the sensor measurements. The spectrum was then divided into frequency zones based on the general characteristic and magnitudes of the peaks within the zone (Figure 5-2). The frequency zones also considered evidence from other plant measurements for which digitized plant measurement information was not available. [[

]]. The magnitude of the reference load in each frequency zone was set equal to the maximum peak value within the zone. The steamline velocity for the plant setting the magnitude of the load was also identified as the reference velocity for scaling purposes.

[[

]].

### *5.1.2 Plant-Specific Scaling Process*

For the plant-specific evaluation, the reference load in each frequency zone was scaled based on the ratio of the plant-specific steamline flow velocity to the reference steamline flow velocity. It should be noted that [[

]]. For the process used in the plant-specific applications, the frequency zones associated with the reference load definition are the ones that continue to be used for the plant-specific evaluation. The plant-specific load amplitudes were determined for each frequency zone by using the following generic equations:

[[

The scaling results using the Reference load amplitudes to derive the BFNP load amplitudes for both OLTP and EPU conditions are shown in Table 5-1 and Figure 5-3.

### 5.2 ASME Loads and Load Combinations

The dryer is a non-safety class and Non-Seismic Category I component. Therefore, the steam dryer needs only to be analyzed for those faulted load combinations for which a steam dryer failure could interface with the required performance of safety class equipment (i.e., closure of Main Steam Isolation Valves (MSIVs)). However, in light of the Quad Cities experience, efforts have been made to evaluate the relevant dryer loads, load combinations and acceptance criteria as if the dryer were a safety component in order to determine locations of high stress under these conditions.

### 5.2.1 *Loads Acting on the Steam Dryer*

The generic definitions of static and dynamic loads that are potentially acting on the steam dryer are described in this section. Section 5.2.2 then describes the specific load combinations and loads used in the BFNP dryer analysis.

<u>Static Loads:</u>

<u>Differential Pressure (DP):</u> The operating pressure differentials across each dryer component were based on the CFD analysis. The DP loads assumed in the analysis depend on the service condition and event being analyzed.

<u>Deadweight (DW):</u> Weight of the dryer components must be considered.

<u>Thermal Expansion:</u> The steam temperature at each dryer component is the same. The RPV transient temperature changes for all operating events are mild. The materials for the dryer components are of the same type of stainless steel and, therefore, have the same thermal expansion coefficient. Although the RPV is carbon steel and has a lower thermal expansion coefficient, the dryer ring support is not radially constrained by the RPV; therefore, the loads due to thermal expansion effects on the dryer are negligible and do not need to be analyzed.

<u>Dynamic Loads:</u>

<u>Flow Induced Vibration (FIV):</u> The primary concern for the dryer structure is fatigue failure of the components from the FIV loading during normal operation. There are two potential sources of flow induced vibration loads on the dryer. The first load is an acoustic pressure loading caused by the steam flow through the steam piping system. [[

]]. The second load is turbulent buffeting caused by the steam flow through and across the dryer structure. [[

]].

<u>Seismic</u>: Seismic, operating basis earthquake (OBE) and safe shutdown earthquake (SSE), responses in the form of amplified response spectra (ARS) at the reactor dryer support elevation are used in accordance with the data documented in seismic loads evaluations. The analysis considers only the effects due to inertia force. An equivalent static analysis was performed for

the inertia forces. Seismic anchor motion effects do not need to be considered because they are negligible inside the reactor pressure vessel (RPV).

Turbine Stop Valve (TSV) Loads: A turbine stop valve closure produces two loads on the dryer. The first load (TSV1) is due to the impact of the acoustic pressure wave created by the valve closure. This wave travels at sonic velocity toward the RPV through each steamline. Repeated reflection of the pressure wave between the dryer face and vessel wall produces time varying pressures and velocities throughout the MS lines. The pressure wave distribution on the outer front hood is considered in the analysis. The second load (TSV2) is caused by the inertial impact of the flow reversal in the steamline. [[

]].

SRV Related Loads: The opening of the safety relief valves during a transient can result in loads on the dryer directly through the resulting pressure effects in the steamline and indirectly by transmission of the discharge loads through the containment structure and RPV. The flow transient produced by rapid opening of the SRVs generates a decompression wave in the main steam line that impacts the RPV dryer. [[

]]. The differential pressure loads related to the increase in steamline flow when the relief valves are opened are addressed in the upset condition evaluations.

The SRV discharge flow to the suppression pool causes containment vibrations that may be transmitted through the containment structure and reactor vessel to the RPV internals, thus creating a load on the dryer components. [[

]].

Loss-Of-Coolant Accident (LOCA) Loads: A Loss-of-Coolant accident subjects the steam dryer to several loads, both directly and indirectly. The LOCA directly affects the differential pressure loads on the dryer. In addition, loads resulting from the pipe break may act on the RPV, which are then transmitted to the dryer. Containment loads resulting from the vessel blowdown may also be transmitted through the RPV to the dryer. These loads are discussed below.

Differential Pressure (DP): For large steamline breaks, the rapid vessel depressurization results in flashing of the water in the reactor vessel. The resulting two-phase mixture swells and impacts the dryer, resulting in high differential pressure loads. [[

]].

Jet Reaction (JR): This load is caused by the break flow escaping through a vessel nozzle. These loads act on the RPV and may be transmitted to the dryer.

Annulus Pressurization (AP): A break in the feedwater or recirculation loop piping releases mass and energy into the annular subcompartment between the reactor vessel and biological shield wall. The resulting asymmetrical pressurization places a dynamic load on the RPV. Additional dynamic loads considered as part of the AP loads result from the jet reaction, jet impingement and pipe whip restraint forces that are induced on the RPV and shield wall. These loads act on the RPV and may be transmitted to the dryer.

Containment Loads During a LOCA: Dynamic loads during a LOCA that result from the vessel blowdown to the suppression pool cause loads that may be transmitted through the containment structure and reactor vessel to the RPV internals, thus creating loads on the dryer components. These loads include pool swell, vent thrust, condensation oscillation, and chugging. [[

]].

### 5.2.2 *ASME Load Combinations for BFNP*

The loads described in the preceding section were reviewed to determine the loads and load combinations to be considered in the BFNP steam dryer analyses. Browns Ferry is not a "New Loads" plant; therefore, annulus pressurization and jet reaction loads are not part of the design and licensing basis for the plant and are not considered in these load combinations. The resulting load combinations for each of the service conditions are summarized in Table 5-2.

The steam dryer structural analyses consider the transient and accident events listed in Browns Ferry UFSAR Tables 14.4-1 and 14.4-2. The transient and accident events that are of particular interest for the evaluation of reactor internal pressure difference (RIPD) loading on vessel internals are events with one or more of the following characteristics: 1) pressurization, 2) depressurization, 3) core coolant flow increase, or 4) moderator temperature decrease. The load combinations for the limiting transient and accident events evaluated are listed in Table 5-1. The turbine stop valve closure transient (Upset 1 and Upset 2 in Table 5-1) is the limiting transient event for reverse pressure loading on the dryer. The Upset 3 load case bounds the remaining transient events. The Faulted 1 and Faulted 2 load cases address the main steamline break accident outside containment (the design basis event for the dryer). The Faulted 3 load cases address the remaining loss of coolant accidents. [[

]].

Each of the load combination cases is briefly discussed below:

Normal: The deadweight, normal differential pressure, and FIV loads are combined for the normal service condition. The deadweight load is calculated internally in the FEA model based on the solid volume of the components and density of the materials. The average differential pressures across the components range from [[ ]] (Table 5-4). There is a significant pressure variation across the outer vertical hood. The pressure distribution assumed in the analysis (based on the CFD calculations) is shown in Figure 5-4. The FIV loads (FIVn) are shown in Figure 5-3 and given in Table 5-1.

Upset 1: This load combination represents the acoustic wave portion of the turbine stop valve closure transient (TSV1). [[

]]. The acoustic wave pressure distribution (TSV1) is given in Table 5-3. Deadweight and OBE seismic loads are also included. The OBE seismic loads are documented in References 2 and 3.

Upset 2: This load combination represents the flow impingement portion of the turbine stop valve closure transient (TSV2). The TSV2 load on the dryer face at EPU is [[

]].

Deadweight and OBE seismic loads are also included. The OBE seismic loads are documented in References 2 and 3.

Upset 3: This load combination bounds the other transient events. [[

]]. The scaled differential pressures used in the analysis are shown in Table 5-5. [[

]].

Deadweight and OBE seismic loads are also included. The OBE seismic loads are documented in References 2 and 3.

Faulted 1: This load combination is for the main steamline break outside containment accident with the reactor at full power. The faulted differential pressure load (DPf) represents the loading due to the two-phase level swell impacting the dryer. [[

]].

Deadweight and SSE seismic loads are also included. The SSE seismic loads are documented in References 2 and 3.

Faulted 2: This load combination is for the main steamline break outside containment accident with the reactor at low power/high core flow (interlock) conditions. The faulted differential pressure load (DPf) represents the loading due to the two-phase level swell impacting the dryer. A value of [[ ]] was used for DPf. [[

]]. Deadweight loads are also included.

Faulted 3: This load combination is for pipe breaks other than the main steamline break. [[

]].

Deadweight and SSE seismic loads are also included. The SSE seismic loads are documented in References 2 and 3.

# 6. STRUCTURAL EVALUATION

## 6.1 Evaluation of the Component Natural Frequencies

For use in deriving the pressure amplitude for application using "Equivalent Static Method", frequency calculations were performed with the dryer supported from the RPV dryer support brackets. The support was modeled by fixing all degrees of freedom at the dryer hold down interface. The entire dryer was surveyed for the component natural frequencies. The representative mode shapes for these selected components are shown in Figures 6-1 through 6-9.

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Acceptable convergence was achieved between the Rayleigh frequencies and the computed natural frequencies as selectively shown in Figures 6-1 through 6-9. The proximity of the results also indicates the adequacy of the mesh size for the natural frequency calculations, since the energy calculations are based on the deformed shape. It is worth noting that both approaches lead to the use of the same stress scaling factors used by the Equivalent Static Method.

## 6.2 Static Stress Evaluation Based on 3-D Whole Dryer Model and ASME Load Combinations

Based on the scale model test results, the fluctuating pressure loads on the inner banks are significantly lower than the loads on the front face of the dryer and for purposes of the analysis were conservatively assumed to be 50% of those on the outer banks. A [[ ]] pressure load was applied across the outer hood dryer surfaces. A pressure load of [[ ]] was applied across the inner bank dryer surfaces. Analyses for unit pressure loads were performed using the same analysis model as used for frequency calculations.

The calculated stress distributions for this pressure load are shown in Figures 6-10 through 6-17. The maximum stress values in different components are summarized in the Table 6-1. These values will be discussed in the context of the equivalent static scaling process in Section 7.0. The BFNP steam dryer is a non-safety component. Therefore, at the time of the original fabrication there were and still are no specific Code requirements for the dryer as to the design margin under the applicable load combinations. Tables 6-2, 6-3, 6-4 and 6-5 detail the calculated stresses for the load cases discussed in Section 5.2. Based on the ANSYS results, the dryer meets the

Service Level A acceptance criteria (including the FIV loads). For Service Level B, the outer hood components do not pass the screening criteria for the TSV closure event (Upset 1). These results are consistent with plant operating experience where minor denting has been observed in the hood panels directly across from the steamlines. This denting does not jeopardize the overall structural integrity of the dryer. For Service Level D, the inner hood vertical stiffener did not pass the screening criteria. A more detailed evaluation of this location should be performed as part of the modification analyses. The inner hood stiffener will be constrained within the dryer structure and cannot enter the steamline. Therefore, failure of this component during a faulted event will not prevent the MSIVs from closing during the accident

# 7. STEAM DRYER STRUCTURAL EVALUATION FOR FIV-INDUCED FATIGUE SUSCEPTIBILITY

## 7.1 Overview of Static Evaluation Process

For the EPU evaluation, GENE developed a process to evaluate the steam dryer dynamic vibration response to assess vulnerability to FIV-induced fatigue. This process is based on the BFNP specific scaled load definition (detailed in section 5.1.2), the natural frequency assessment based on the ANSYS dryer model and the resultant stresses based on the application of a normalized pressure load to all pressure bearing surfaces. The method is termed "Equivalent Static Analysis Method." The Equivalent Static Analysis Method consists of the following process steps:

1. A Finite Element Analysis (FEA) model of the BFNP steam dryer is developed. This model is constructed using BFNP specific dryer dimensions and material properties.

2. The FEA computes steam dryer component natural frequencies and mode shapes. Fundamental natural frequencies for all components of interest are computed by using the Rayleigh's method to identify the predominant vibration mode for the components.

3. A unit static pressure load is applied in the FEA model. Steam Dryer component Membrane (Pm) and Surface (Pm + Pb) stresses are computed from the applied unit load.

4. Dynamic Stress (DS) on the steam dryer components is computed via the following equation:

DS = (Pm+Pb) x (FIV Load rms) x (P) x (SF) x (C)

Where:

DS = Dynamic Stress (psi)

Pm+Pb = Surface stress computed from [[ ]] static load in FEA model ([[ ]] for outer bank components, and [[ ]] for inner bank components)

FIV Load rms = Fluctuating load (Root-mean-squared (rms) load amplitude) obtained from plant measured data and scaled to BFNP steam velocity for OLTP and LPU conditions. Also it is component frequency dependent. See Section 5.1 for the detailed discussion.

P = Peak factor for load to convert rms amplitude to Peak amplitude. For a pure single frequency sinusoidal time function, the peak is equal to $\sqrt{(2)}$ times the rms amplitude. For the flow induced vibration time function of reactor internal components, a factor of [[ ]] is commonly used by GENE to account for the summation of many frequencies.

C = Stress Concentration Factor including the weld quality factor. The FEM calculated peak stress has picked up some of the stress concentration factor. A C value of [[ ]] is used based on good shop quality welds and the inspection techniques typically used in dryer fabrication.

SF = Scaling Factor (or Dynamic Scaling factor). Factor typically observed to vary from [[ ]]. The determination of SF is given in the in the following.

The evaluation process assumes that the no components have failed at OLTP condition and, therefore have a peak stress value no larger than fatigue endurance limit (13,600 psi). The Scaling Factor (SF) is back-calculated from the highest stressed components under OLTP condition using the following equation:

$$SF = \frac{13{,}600}{(Pm + Pb)(FIVLoadrms)(P)(C)}$$

The dynamic stresses under EPU condition are then calculated based on step 4 and the above calculated SF. Components that are susceptible to stress fatigue failure are then identified as the dynamic stress exceeds the fatigue endurance limit.

At BFNP, the weld at the outer cover plate to hood slanted plate is a fillet weld of size 1/4-inch, which is smaller than the 3/8-inch thickness of the cover plate. Thus, an additional factor needs to be applied when calculated the peak dynamic stress at this undersized weld to accounts for the undersized effect. This factor will be dependent on the actual loading pattern at the weld location. A factor of 2.25 is selected for the present analysis, which is based on the fact that the dominant load in the cover plate is of a bending type, and bending-induced stresses are inversely proportional to the thickness ratio to the square power, if the effect of the off-center between the plate and weld is neglected.

### 7.2 BFNP Dryer Equivalent Static Assessment

Based on the above discussed static assessment process, the highest stressed component of the BFNP steam dryer under OLTP condition is the outer cover plate weld. By scaling this outer-cover-plate weld stress to the endurance limit of 13,600 psi, a scaling factor of [[ ]] is calculated. This [[ ]] scaling factor is then applied to calculate the dynamic stresses for all of the other components, and to also calculate the dynamic stresses under EPU condition.

Table 7-1 lists the peak dynamic stresses of the BFNP stream dryer under both OLTP and EPU conditions. The outer cover plate weld is identified as the component that is most susceptible to FIV stress induced fatigue under EPU condition.

### 7.3 Dynamic Method for Evaluation of FIV-Induced Fatigue Susceptibility

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]].

Shown in Figures 7-1 through 7-3 are pressure spectra, synthetic pressure time histories, and response spectra from the peak pressure measurements of three plants (one domestic plant and two foreign plants) scaled to the BFNP OLTP condition. Figure 7-4 presents the enveloping and further broadened response spectrum. Similarly, shown in Figures 7-5 through 7-8 are three response spectra, synthetic pressure time histories, response spectra and the enveloping response spectrum for the BFNP EPU condition. Note that, in the figures, the input pressure spectra are given in rms amplitude. The corresponding synthetic pressure time histories, and response spectra and enveloping response spectrum are expressed in Peak amplitude, where a peak factor of 3 to covert rms amplitude to Peak amplitude has been incorporated.

Based on the response spectrum method, ANSYS calculated component stress distributions for the BFNP OLTP conditions are shown in Figures 7-9 through 7-16. The SRSS (square root of the sum of the squares) method of the ANSYS modal combination is used to obtained these stress results.

Next, these stresses need to be multiplied by the appropriate stress concentration factor (2.25) to account for the 1/4-inch weld on the 3/8 inch plate and weld quality factor ([[ ]]) to arrive at the peak dynamic stress at the corresponding locations.

Under OLTP condition, of all the outer bank components, the highest stress is at the outer cover plate weld. By scaling this outer cover plate weld stress to the endurance limit of 13,600 psi, a scaling factor of [[ ]] is calculated. This [[ ]] scaling factor is then applied to calculate the dynamic stresses of all other components, and also to calculate the dynamic stresses under EPU condition.

Table 7-1 lists the peak dynamic stresses of the BFNP stream dryer under OLTP and EPU conditions. The outer cover plate weld, outer hood stiffener and inner hood stiffener are identified as the components that are most susceptible to FIV-induced fatigue under EPU conditions.

### 7.4 Summary of BFNP Dryer to FIV-Induced Fatigue Susceptibility

Based on the present FIV-induced fatigue assessment at EPU conditions, the most vulnerability location is at the outer cover plate 1/4-inch weld location as identified by both the equivalent static and the response spectrum methods. The response spectrum method further identifies the outer hood stiffeners and the inner hood stiffeners as susceptible locations at EPU conditions. The inner hood stiffener susceptibility is very dependent on the assumed pressure loading which was half of the outer bank pressure spectrum as used in the present evaluation. However, it should be noted that no failures, at uprated plants, have been observed on the inner hood stiffeners.

## 8. SUSCEPTIBLE LOCATIONS

The objective of this work has been to quantify the high stress locations in the BFNP dryer and to review the impact of EPU conditions on the stress magnitudes at these identified locations. The report also has the objective of evaluating the existing indications in BFNP Units 1, 2 and 3.

### 8.1 Outer Cover Plate and Outer Hood Assessments

As has been discussed, the approach focused on the stresses produced by the fluctuating pressure loading in the outer cover plate, the outer hood slanted plate and the outer hood top and end plates. These fluctuating loads are always present during normal operation. The assessment made use of a 3-D whole dryer finite element model to predict the stresses. Both equivalent static and dynamic response spectrum methods were used. As discussed in section 7.0, the outer cover plate weld is considered vulnerable to FIV fatigue failure at EPU. All of the evaluations support this conclusion. At EPU conditions, the response spectrum method also predicts peak stresses that are high enough to lead to fatigue concerns at the outer hood and inner hood stiffeners. These locations merit additional evaluation.

### 8.2 Disposition of Existing Cracking

As stated in the introduction, previous inspections have identified cracking in both BFNP Unit 1 and BFNP Unit 2. Tables 8-1 and 8-2 summarize these findings.

# 9. CONCLUSIONS AND RECOMMENDATIONS

The analysis of BFNP steam dryer analysis has been used to identify the high stress locations in the outer portions of the structure. The model, the analysis methods and the findings have been presented in the previous sections. The modeling results establish that the outer cover plate has higher susceptibility to fluctuating loads that could lead to fatigue crack initiation in the weld region between the cover plate and the outer hood. Additionally, the analyses do show that the outer hood and inner hood stiffener locations could have some risk of fatigue over time at EPU conditions.

Based on these analyses, the following recommendations should be considered.

1. The outer cover plate weld should be strengthened. This could be (1) potentially accomplished by building up the weld to 3/8-inch and adding a vertical gusset or (2) by replacing the outer cover plate and weld with ½-inch thick plate and weld and adding a gusset. This location needs to be mitigated to prevent any risk of fatigue damage
2. The outer hood and inner hood stiffener locations are also regions of higher stress at EPU conditions. The magnitude of the stress is a function of the assumptions regarding scaling factors and pressure loading. Therefore, it is recommended that actions be taken to further evaluate the fluctuating stresses prior to extending power to a 120% EPU.
3. Finally, it is recommended that the tie bars be preemptively replaced with larger ones to preclude fatigue cracking in the future. This type of repair has been implemented in several plants successfully.

## 10. REFERENCES

1. "SPECA05V User's Manual", GENE NEDE-25181, Class 2, August 1996.
2. Bechtel Report "Recalculation of Seismic Responses for Reactor Building, Drywell and Internals of Browns Ferry Nuclear Plants using El Centro Time History Input," dated August 7, 1989}
3. TVA Report CEB 88-05-C Revision 1, "Browns Ferry Nuclear Plant MARS Report Seismic Class 1 Structures".

**Table 5-1: Fluctuating Pressure Loads (Normal Condition)**

| Frequency Zone, Hz | Reference Amplitude, rms psi. | Reference Steamline Flow Velocity*, ft/sec | Maximum Scaling Exponent | Minimum Scaling Exponent | Pressure Amplitude (OLTP), rms psi. | Pressure Amplitude (LPU), rms psi. |
|---|---|---|---|---|---|---|
| 0-55 | [[ | | | | | |
| 55-120 | | | | | | |
| 120-205 | | | | | | |
| 205-320 | | | | | | |
| 320-525 | | | | | | |
| 525-800 | | | | | | ]] |

*Flow velocity from in-plant test measurements for the plant defining the reference amplitude in each frequency range

BFNP steamline flow velocity:

OLTP: 128 ft/sec

EPU: 157 ft/sec

[[

]]

**Table 5-2: Load Combinations for BFNP Steam Dryer Analysis**

| Service Condition | Load Combination | Screening Criteria (Note 1) | Fatigue Acceptance Criteria |
|---|---|---|---|
| Normal | DW + DPn + FIVn | Pm ≤ 1.0 Sm<br>(Pm + Pb) ≤ 1.5 Sm | FIVn <13,600 psi<br>Note 3 |
| Upset 1 | DW + DPn + [ $TSV1^2 + OBE^2$ ]$^{1/2}$ + FIVn | Pm ≤ 1.0 Sm<br>(Pm + Pb) ≤ 1.5 Sm | FIVn <13,600 psi<br>Notes 2 and 3 |
| Upset 2 | DW + DPn + [ $TSV2^2 + OBE^2$ ]$^{1/2}$ | Pm ≤ 1.0 Sm<br>(Pm + Pb) ≤ 1.5 Sm | Not Applicable |
| Upset 3 | DW + DPu + OBE + FIVu (Note 4) | Pm ≤ 1.0 Sm<br>(Pm + Pb) ≤ 1.5 Sm | FIVu < 13,600 psi<br>Notes 2 and 3 |
| Faulted 1 | DW + [ $DPf1^2 + SSE^2$ ]$^{1/2}$ | Pm ≤ 2.4 Sm<br>(Pm + Pb) ≤ 3.6 Sm | Not Applicable |
| Faulted 2 | DW + DPf2 | Pm ≤ 2.4 Sm<br>(Pm + Pb) ≤ 3.6 Sm | Not Applicable |
| Faulted 3 | DW + DPn + SSE | Pm ≤ 2.4 Sm<br>(Pm + Pb) ≤ 3.6 Sm | Not Applicable |

Notes:

1. These criteria are for screening purposes and are not requirements for the dryer components.
2. These transient events are of a short duration; therefore, fatigue is not a critical consideration.
3. The value of 13,600 psi is based on austenitic stainless steel.
4. The relief valve opening decompression wave load is bounded by the TSV loads (Upset 1); therefore, this load is not explicitly included in the dryer analysis

## Table 5-2: Load Combinations for BWR/3/4 Steam Dryers (cont.):

**(Definitions and Note explanations)**

| | |
|---|---|
| DW | = Dead Weight. |
| DPn | = Differential Pressure Load During Normal Operation. |
| DPu | = Differential Pressure Load During Upset Operation. |
| DPf1 | = Differential Pressure Load in the Faulted condition, due to Main Steam Line Break Outside Containment at the Rated Power and Core Flow (Hi-Power) condition. |
| DPf2 | = Differential Pressure Load in the Faulted condition, due to Main Steam Line Break Outside Containment at the Low Power/High Core Flow (Interlock) condition. |
| FIVn | = Flow Induced Vibration Load (zero to peak amplitude of the response) during Normal Operation. |
| FIVu | = Flow Induced Vibration Load (zero to peak amplitude of the response) during Upset Operation. |
| OBE | = Operating Basis Earthquake. |
| SSE | = Safe Shutdown Earthquake. |
| TSV1 | = The Initial Acoustic Component of the Turbine Stop Valve (TSV) Closure Load. (Inward load on the outermost hood closest to the nozzle corresponding to the TSV closure) |
| TSV2 | = The Flow Impingement Component (following the Acoustic phase) of the TSV Closure Load; (Inward load on the outermost hood closest to the nozzle corresponding to the TSV closure). |

Notes:

(1) The load combinations shown are generic to the steam dryers of BWR/3/4 Non-*New Loads* Plants.

(2) The load combinations are consistent with the Load Combinations and Acceptance Criteria document 386HA624, Revision 2.

(3) The steam dryer is a non-safety related component, not requiring mandatory code compliance, per the original design basis. Even though the ASME code allowables are identified, the primary safety requirement is that no loose parts are created that could impair the ECCS functions or safe shutdown of the reactor during any of the operating conditions.

**Table 5-3: Maximum Acoustic Load (TSV1) on the Dryer Face at EPU**

| y, Dryer Vertical Centerline | Pressure Differential (psid) | | | | | |
|---|---|---|---|---|---|---|
| [[ | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | ]] |

## Table 5-4: Pressure Differentials for Normal Conditions at EPU (DPn)

| Description | Value[1] (psid) |
|---|---|
| Outer Hood Slanted Plate | [[ |
| Outer Cover Plate | |
| Outer Hood Top Plate | |
| Inner Hood Top Plate | |
| Vertical Section of Inner Hood | ]] |

* Average pressure differential over outer slanted vertical hood plate.

Pressure distribution used based on distribution shown in Figure 5-4.

**Table 5-5: Pressure Differentials for Upset 3 Conditions at EPU (DPu)**

| Description | Value (psid) |
|---|---|
| Outer Hood Slanted Plate | [[ |
| Outer Cover Plate | |
| Outer Hood Top Plate | |
| Inner Hood Top Plate | |
| Vertical Section of Inner Hood | ]] |

* Average pressure differential over outer slanted vertical hood plate.

Pressure distribution used based on distribution shown in Figure 5-4

**Table 6-1: Steam Dryer Component Associated Frequencies and Unit-psi Reference Load Stresses for Use in the Equivalent Static FIV Evaluation Method**

| Component | Unit psi Pm+Pb | Associated Frequency | OLTP Amplitude, rms (psi) | EPU Amplitude, rms (psi) |
|---|---|---|---|---|
| **Outer hood slanted plates** | [[ | | | |
| **Outer hood top plates** | | | | |
| **Outer hood end plates** | | | | |
| **Outer hood stiffeners** | | | | |
| **Outer cover plate** | | | | |
| **Inner hood slanted plates** | | | | |
| **Inner hood top plates** | | | | |
| **Inner hood end plates** | | | | |
| **Inner hood stiffeners** | | | | |
| **Inner cover plates** | | | | |
| **Steam dam** | | | | |
| **Steam dam gussets** | | | | |
| **Baffle plate** | | | | ]] |

**Table 6-2: BFNP Steam Dryer ASME OLTP Load Combination Compliance with FIV Included as Equivalent Static Method**

| Operating condition | Service Level A | | Service Level B | | | | | | Service Level D | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Component | Normal Pm, psi | Normal Pm+Pb, psi | Upset 1 Pm, psi | Upset 1 Pm+Pb, psi | Upset 2 Pm, psi | Upset 2 Pm+Pb, psi | Upset 3 Pm, psi | Upset 3 Pm+Pb, psi | Faulted 1 Pm, psi | Faulted 1 Pm+Pb, psi | Faulted 2 Pm, psi | Faulted 2 Pm+Pb, psi | Faulted 3 Pm, psi | Faulted 3 Pm+Pb, psi |
| Outer hood slanted plates | [[ | | | | | | | | | | | | | |
| Outer hood top plates | | | | | | | | | | | | | | |
| Outer hood end plates | | | | | | | | | | | | | | |
| Outer hood stiffeners | | | | | | | | | | | | | | |
| Outer cover plate | | | | | | | | | | | | | | |
| Inner hood slanted plates | | | | | | | | | | | | | | |
| Inner hood top plates | | | | | | | | | | | | | | |
| Inner hood end plates | | | | | | | | | | | | | | |
| Inner hood stiffener | | | | | | | | | | | | | | |
| Inner cover plates | | | | | | | | | | | | | | |
| Steam dam | | | | | | | | | | | | | | |
| Steam dam gussets | | | | | | | | | | | | | | |
| Baffle plate | | | | | | | | | | | | | | ]] |

**Table 6-3: BFNP Steam Dryer ASME EPU Load Combination Compliance with FIV Included as Equivalent Static Method**

| Operating condition | Service Level A | | Service Level B | | | | | | Service Level D | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Component | Normal Pm, psi | Normal Pm+Pb, psi | Upset 1 Pm, psi | Upset 1 Pm+Pb, psi | Upset 2 Pm, psi | Upset 2 Pm+Pb, psi | Upset 3 Pm, psi | Upset 3 Pm+Pb, psi | Faulted 1 Pm, psi | Faulted 1 Pm+Pb, psi | Faulted 2 Pm, psi | Faulted 2 Pm+Pb, psi | Faulted 3 Pm, psi | Faulted 3 Pm+Pb, psi |
| Outer hood slanted plates | [[ | | | | | | | | | | | | | |
| Outer hood top plates | | | | | | | | | | | | | | |
| Outer hood end plates | | | | | | | | | | | | | | |
| Outer hood stiffeners | | | | | | | | | | | | | | |
| Outer cover plate | | | | | | | | | | | | | | |
| Inner hood slanted plates | | | | | | | | | | | | | | |
| Inner hood top plates | | | | | | | | | | | | | | |
| Inner hood end plates | | | | | | | | | | | | | | |
| Inner hood stiffener | | | | | | | | | | | | | | |
| Inner cover plates | | | | | | | | | | | | | | |
| Steam dam | | | | | | | | | | | | | | |
| Steam dam gussets | | | | | | | | | | | | | | |
| Baffle plate | | | | | | | | | | | | | | ]] |

**Table 6-4: BFNP Steam Dryer ASME OLTP Load Combination Compliance with FIV Included as Response Spectrum Analysis**

| Operating condition | Service Level A | | Service Level B | | | | | | Service Level D | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Component | Normal Pm, psi | Normal Pm+Pb, psi | Upset 1 Pm, psi | Upset 1 Pm+Pb, psi | Upset 2 Pm, psi | Upset 2 Pm+Pb, psi | Upset 3 Pm, psi | Upset 3 Pm+Pb, psi | Faulted 1 Pm, psi | Faulted 1 Pm+Pb, psi | Faulted 2 Pm, psi | Faulted 2 Pm+Pb, psi | Faulted 3 Pm, psi | Faulted 3 Pm+Pb, psi |
| Outer hood slanted plates | [[ | | | | | | | | | | | | | |
| Outer hood top plates | | | | | | | | | | | | | | |
| Outer hood end plates | | | | | | | | | | | | | | |
| Outer hood stiffeners | | | | | | | | | | | | | | |
| Outer cover plate | | | | | | | | | | | | | | |
| Inner hood slanted plates | | | | | | | | | | | | | | |
| Inner hood top plates | | | | | | | | | | | | | | |
| Inner hood end plates | | | | | | | | | | | | | | |
| Inner hood stiffener | | | | | | | | | | | | | | |
| Inner cover plates | | | | | | | | | | | | | | |
| Steam dam | | | | | | | | | | | | | | |
| Steam dam gussets | | | | | | | | | | | | | | |
| Baffle plate | | | | | | | | | | | | | | ]] |

**Table 6-5: BFNP Steam Dryer ASME EPU Load Combination Compliance with FIV Included as Response Spectrum Analysis**

| Operating condition | Service Level A | | Service Level B | | | | | | Service Level D | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Component | Normal Pm, psi | Normal Pm+Pb, psi | Upset 1 Pm, psi | Upset 1 Pm+Pb, psi | Upset 2 Pm, psi | Upset 2 Pm+Pb, psi | Upset 3 Pm, psi | Upset 3 Pm+Pb, psi | Faulted 1 Pm, psi | Faulted 1 Pm+Pb, psi | Faulted 2 Pm, psi | Faulted 2 Pm+Pb, psi | Faulted 3 Pm, psi | Faulted 3 Pm+Pb, psi |
| Outer hood slanted plates | [[ | | | | | | | | | | | | | |
| Outer hood top plates | | | | | | | | | | | | | | |
| Outer hood end plates | | | | | | | | | | | | | | |
| Outer hood stiffeners | | | | | | | | | | | | | | |
| Outer cover plate | | | | | | | | | | | | | | |
| Inner hood slanted plates | | | | | | | | | | | | | | |
| Inner hood top plates | | | | | | | | | | | | | | |
| Inner hood end plates | | | | | | | | | | | | | | |
| Inner hood stiffener | | | | | | | | | | | | | | |
| Inner cover plates | | | | | | | | | | | | | | |
| Steam dam | | | | | | | | | | | | | | |
| Steam dam gussets | | | | | | | | | | | | | | |
| Baffle plate | | | | | | | | | | | | | | ] |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | ] |

1) $P_N$: normal operation RIPD $P_U$: upset condition RIPD $P_F$ : faulted condition RIPD

2) Dryer frequencies (except the center plate frequency) exceed [[ ]]. Therefore seismic loads applied as ZPA loads in equivalent static analyses.

Horizontal excitations parallel and perpendicular to the dryer banks ([[ ]]) and vertical excitation ([[ ]]) were applied simultaneously. The results were combined with the results from the earthquake response spectrum analysis following the SRSS rule.

The ± operators in (Weight ± OBE) and (Weight ± DBE) load combinations apply to load cases with weight and vertical seismic excitations acting in the same direction and opposite direction. The stress values in the table are the larger of the stresses calculated for the two directions.

3) Stress limits:

| | $P_M$ limit | $P_M + P_B$ limit |
|---|---|---|
| Service Levels A/B | 16900 psi. | 25350 psi. |
| Service Level D | 40560 psi. | 60840 psi. |

4) All the stresses listed are the stress in the plate. The membrane stress, Pm, listed in the above table is the peak of membrane stress, not general membrane stress. Pm+Pb is also the peak values. The above limits apply to general membrane stress and general membrane plus bending stress.

## Table 7-1 Steam Dryer FIV-Induced Stresses and Fatigue Susceptibility

| | Equivalent Static Analysis (Unit psi scaling) | | | | Full Dryer Response Spectrum Analysis | | | |
|---|---|---|---|---|---|---|---|---|
| Amplification factor | [[ | | | | | | | ]] |
| Component | OLTP | Fatigue criterion test | EPU | Fatigue criterion test | OLTP | Fatigue criterion test | EPU | Fatigue criterion test |
| Outer hood slanted plates | [[ | | | | | | | |
| Outer hood top plates | | | | | | | | |
| Outer hood end plates | | | | | | | | |
| Outer hood stiffener weld | | | | | | | | |
| Outer cover plate weld# | | | | | | | | |
| Inner hood slanted plates | | | | | | | | |
| Inner hood top plates | | | | | | | | |
| Inner hood end plates | | | | | | | | |
| Inner hood stiffener weld | | | | | | | | |
| Inner cover plates | | | | | | | | |
| Steam dam | | | | | | | | |
| Steam dam gussets | | | | | | | | |
| Baffle plate | | | | | | | | ]] |

** Note: Dynamic Scaling Factor (SF) of [[ ]] is used for both OLTP and EPU Equivalent Static Method calculation, and [[ ]] is used for both OLTP and EPU Response Spectrum Method calculation.

\# Reduced Weld Factor of [[ ]] included for both OLTP and EPU calculation.

## Table 8-1: BFNP Unit 1 Steam Dryer Inspection Data and Disposition for EPU

| Location | Year | Indication | Disposition for EPU | Reason for Disposition |
|---|---|---|---|---|
| [[ | | | | ]] |

## Table 8-2: BFNP Unit 2 Steam Dryer Inspection Data and Disposition for EPU

| Location | Year | Indication | Disposition for EPU | Reason for Disposition |
|---|---|---|---|---|
| [[ | | | | |
| | | | | |
| | | | | ]] |

## Table 8-3: BFNP Unit 3 Steam Dryer Inspection Data and Disposition for EPU

| Location | Year | Indication | Disposition for EPU | Reason for Disposition |
|---|---|---|---|---|
| [[ | | | | |
| | | | | |
| | | | | ]] |

Note: Drain channels have cracked during normal operation and may crack at EPU. Additional weld material will minimize the probability of cracking. Drain channel cracking has never led to an unplanned plant shutdown and can be repaired during an outage.

[[

]]

**Figure 4-1 BFNP Steam Dryer Components: Support Ring, Base Plates and Troughs.**

[[

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**Figure 4-2 BFNP Steam Dryer Components: Details of the Support Ring, Trough with Hood Stiffeners Added.**

[[

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**Figure 4-3 BFNP Steam Dryer Components: Internal Details of the 3-D Model.**

[[

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**Figure 4-4 BFNP Steam Dryer Components: Addition of End plates.**

[[

]]

**Figure 4-5 BFNP Steam Dryer Components: Outer Hood Details and Steam Dam with External Gussets**

[[

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**Figure 4-6: BFNP Steam Dryer Shaded to Provide Overview of the Assembled Structure.**

[[

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**Figure 4-7: BFNP Steam Dryer with Key Components Labeled**

Figure 4-7 Notes: Inner and outer components use the same nomenclature.

The "Hood Slanted Plate" includes the top and bottom vertical sections

[[

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**Figure 5-1: Steam Dryer Fluctuating Loads – Plant Data Maximum Pressures**

[[

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**Figure 5-2: Steam Dryer Fluctuating Loads – Reference Load Definition**

[[

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[[

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[[

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**Figure 6-1: Outer Hood Slanted Plate Mode Shape (f=45 Hz)**

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**Figure 6-2: Outer Hood Slanted Plate Mode Shape (f=58 Hz)**

[[

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**Figure 6-3: Outer Hood Slanted Plate Mode Shape (f=62 Hz)**

[[

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**Figure 6-4: Outer Hood Vertical Plate Mode Shape (f=78 Hz)**

[[

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**Figure 6-5: Outer Hood-Vertical Plate Mode Shape (f=78 Hz)**

[[

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Figure 6-6: Inner Hoods Slanted Plates Mode Shape (f=45 Hz)

[[

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Figure 6-7: Inner Hood Slanted Plate Mode Shape (f=55 Hz)

[[

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Figure 6-8: Inner Hoods Slanted Plates Mode Shape (f=60 Hz)

[[

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Figure 6-9: Cover Plate Mode Shape (f =154 Hz)

[[

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Figure 6-10: Outer Hood Slanted Plates – Normalized Load Averaged Stress

[[

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Figure 6-11: Outer Hood Top Plates – Normalized Load Averaged Stress

[[

]]

**Figure 6-12:Outer Hood End Plates – Normalized Load Averaged Stress**

[[

]]

**Figure 6-13: Outer Hood Stiffeners –Normalized Load Averaged Stress**

[[

]]

**Figure 6-14: Outer Cover Plates – Normalized Load Averaged Stress**

[[

]]

Figure 6-15: Inner Hoods Slanted Plates - Normalized Load Averaged Stress

[[

]]

Figure 6-16: Inner Hoods Top Plates - Normalized Load Averaged Stress

[[

]]

**Figure 6-17. Inner Hoods Endplates - Normalized Load Averaged Stress**

[[

]]

**Figure 6-18. Inner Hood Stiffeners - Normalized Load Averaged Stress**

[[

]]

Figure 6-19. Inner Cover Plates - Normalized Load Averaged Stress

[[

]]

Figure 6-20. Steam Dams - Normalized Load Averaged Stress

[[

]]

[[

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[[

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[[

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[[

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[[

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**Figure 7-6: BFNP EPU Response Spectrum Based on Foreign Plant A Startup Test Data**

[[

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**Figure 7-7: BFNP EPU Response Spectrum Based on Foreign Plant B Startup Test Data**

[[

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[[

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**Figure 7-9: BFNP OLTP Outer Hood Slanted Plate Peak Stress**

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**Figure 7-10: BFNP OLTP Outer Top Hood Plate Peak Stress**

[[

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**Figure 7-11: BFNP OLTP Cover Plate Peak Stress**

[[

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**Figure 7-12: BFNP OLTP Outer Hood End Peak Stress**

[[

]]

**Figure 7-13: BFNP OLTP Inner Hood Stiffeners Peak Stress**

[[

]]

**Figure 7-14: BFNP OLTP Inner Hood Slanted Plate Peak Stress**

[[

]]

**Figure 7-15: BFNP OLTP Inner Hood Slanted Plate Peak Stress**

[[

]]

**Figure 7-16: BFNP OLTP Inner Cover Plate Peak Stress**