ENCLOSURE 2

ATTACHMENT 7

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Quad Cities Units 1 and 2 Replacement Steam Dryer Analysis Stress, Dynamic and Fatigue Analyses for EPU Conditions

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ACRONYMS AND ABBREVIATIONS

Item	Short Form	Description
1	ASME	American Society of Mechanical Engineers
2	BWR	Boiling Water Reactor
3	EPU	Extended Power Uprate
4	FEA	Finite Element Analysis
5	FEM	Finite Element Model
6	FIV	Flow Induced Vibration
7	SCF	Stress Concentration Factor
8	OLTP	Original Licensed Thermal Power
9	ft/sec	Feet per second
10	GE	General Electric
11	GENE	General Electric Nuclear Energy
12	Hz	Hertz
13	IGSCC	Intergranular Stress Corrosion Cracking
14	MS	Main Steam
15	MSL	Main Steam Line
16	Mlbm/hr	Millions pounds mass per hour
17	MW_t	Megawatt Thermal
18	NA	Not Applicable
19	NC	Not Calculated
20	NRC	Nuclear Regulatory Commission
21	OBE	Operational Basis Earthquake
22	Pb	Primary Bending Stress
23	Pm	Primary Membrane Stress
24	psi	Pounds per square inch
25	Re	Reynolds Number
26	Ref.	Reference
27	RMS	Root-Mean-Squared
28	RPV	Reactor Pressure Vessel
29	S	Strouhal Number
30	SIL	Services Information Letter
31	SRSS	Square Root Sum of Squares
32	SRV	Safety Relief Valve

1. EXECUTIVE SUMMARY

In 2002 Quad Cities Unit 2 first developed cracks in the cover plate portion of the steam dryer after the plant had been operating at extended power uprate (EPU). The result of the root cause evaluation showed the primary factor for this event was flow regime instability that resulted in localized, high cycle loadings near the main steam line (MSL) nozzles. Additional cracking was observed in 2003 and 2004 in the cover plate and outer hood portions of the Quad Cities and Dresden steam dryers. A replacement dryer was designed to withstand these flow induced vibration loads. This report summarizes the structural analysis performed to demonstrate the adequacy of this new steam dryer design [1].

Finite element analyses were performed using a whole dryer analysis model of the Exelon replacement dryer to determine the most highly stressed locations associated with EPU. The analyses consisted of time history dynamic analyses, frequency calculations, stress, and fatigue analyses. Two sets of loads were used for the time history analyses. These loads came from plant data measurements and scale model test results. Both the plant data and scale model test results were run through circuit analyses by Continuum Dynamics Inc. (CDI), which supplied pressure time histories to all loaded dryer surfaces in the finite element model [2]. In addition, ASME Code based load cases were also analyzed using the finite element model. The locations of high stress identified in the time history analyses were further evaluated using solid finite element models to more accurately predict the stresses at these locations.

These analyses established that the replacement dryer components are not vulnerable to fatigue at EPU conditions. The replacement dryer satisfies both the fatigue limit and the ASME Code limits for normal, upset and faulted events at EPU conditions [1]. This report summarizes the dynamic, stress and fatigue analyses that demonstrate the Exelon replacement steam dryer is structurally adequate for EPU conditions.

2. INTRODUCTION AND BACKGROUND

2.1 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 rests on the floor of the equipment pool on the lower support ring that is located at the bottom edge of the skirt. Dryers are installed and removed from the RPV using 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 guide channels or upper and lower guides that interface with the guide rods.

Wet steam flows upward from the steam separators into an inlet plenum, horizontally through the dryer vane banks, vertically in an outlet plenum 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 exists below normal water level. The outlet of the drain channels is below the water surface in order to prevent reentrainment of the captured liquid.

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 and later steam dryer designs the active vane height was increased to 72 inches. Perforated plates were included on the inlet and outlet sides

of the vane banks of the 72-inch height units in order to distribute the steam flow uniformly through the bank. The addition of perforated plates resulted in a more uniform velocity over the height of the vanes. The performance for BWR/4 and dryer designs was established by testing in steam.

Most of the steam dryer is located in the steam space, with the lower half of the skirt extending below normal water level. These environments are highly oxidizing. 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 making the steam dryer susceptible to intergranular stress corrosion cracking (IGSCC). Temporary welded attachments may have also been made to the dryer material that could result in unexpected weld sensitized material. Steam dryer parts such as support rings and drain channels were frequently cold formed, also increasing IGSCC 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. Because of the environment and material conditions, most steam dryers have exhibited IGSCC cracking.

Average steam flow velocities through the dryer vanes at OLTP conditions are relatively modest (2 to 4 feet per second). However, the outer hoods near the steam outlet nozzles are continuously exposed to steam flows in excess of 100 feet per second. These flows can excite acoustic resonances in the steam dome and steamlines, resulting in fluctuating pressure loads that act on the dryer.

The dryer is a non-safety class and Non-Seismic Category I component and performs no safety functions. The steam dryer assembly is classified as an "internal structure" per ASME Boiler and Pressure Vessel Code, Section III, Subsection NG. Therefore the steam dryer needs only to be analyzed for those faulted load combinations for which loss of structural integrity of the steam dryer could interfere with the required performance of safety class equipment (i.e., generation of loose parts that may interfere with closure of the MSIVs) or affect the core support structure integrity (shroud, top guide, core support and shroud support).

2.2 Quad Cities and Dresden EPU Dryer Experience

Exelon has experienced dryer cracking and failures at each of the Quad Cities and Dresden units following implementation of Extended Power Uprate (EPU). The first dryer failure, loss of the lower horizontal cover plate at Quad Cities Unit 2, occurred in June 2002 after about three months of EPU operation. The root cause of this failure was determined to be high cycle fatigue due to a high frequency fluctuating pressure load. The second dryer failure, also at Quad Cities Unit 2, occurred in May 2003 after a little more than a year of total EPU operation. This failure consisted of severe through-wall cracking in the outer hood, along with cracking of vertical and diagonal internal braces and tie bars. The root cause of this failure was determined to be high cycle fatigue due to a low frequency fluctuating pressure load. The internal gussets for the diagonal braces created a local stress concentration where the fatigue cracking had initiated. Hood cracking was observed at all four outer hood gusset locations. In October 2003, the dryer at Dresden Unit 2 was inspected following a full two year cycle at EPU conditions. Incipient cracking was observed in the outer hoods at all four diagonal brace gusset locations. In November 2003, Quad Cities Unit 1 experienced a hood failure similar to the one that occurred in May 2003 at Quad Cities Unit 2, again after about a year of EPU operation. Following this failure, Dresden Unit 3, which had been operating at EPU for a little more than one year, was shut and the dryer inspected. Dresden Unit 3 exhibited the same incipient cracking at the outer hood gusset locations as did Dresden Unit 2. In all of these cases, the root cause was determined to be high cycle fatigue due to the fluctuating pressure loads at EPU conditions.

Cracking has also been observed in some of the repairs and modifications that were made to the dryers following these failures. This type of cracking has also been observed to varying degrees in the dryers in all four units. During the March 2004 refueling outage, inspection of the repairs in the Quad Cities Unit 2 dryer showed cracking in the hood plate at the tips of the external gussets on the outer hoods. In November 2004, cracking was observed at one end of the weld between the lower horizontal cover plate and support ring in the Dresden Unit 3 dryer. The lower horizontal cover plate had been replaced in response to the initial 2002 Quad Cities failure as part of the EPU modifications for the dryer. In November 2004, an inspection of the Dresden Unit 2 dryer revealed cracking in the same lower horizontal cover plate weld, this time near the base of one of the external gussets. Recently, a crack was found in this same weld at Quad Cities Unit 1 during a March 2005 inspection, again at the base of one of the external gussets. This cracking experience highlighted the importance of local stress concentrations in determining the fatigue life of the structure. In addition, several of the dryers are beginning to experience fatigue cracking in the perforated plate inserts installed in each dryer as part of the

EPU implementation modifications. Tie bar repairs have also experienced cracking. This experience demonstrates the uncertainty in the useful life of the repairs and modifications performed on the current Quad Cities and Dresden steam dryers.

2.3 Motivation for Additional FIV and Structural Analysis

The experiences at Quad Cities and Dresden demonstrated the need to better understand the nature of the loading and the dynamic structural response of the steam dryers during normal operation. The expense involved with inspection and repair of the dryers for the extended life of the plants provide motivation for determining the loads acting on the dryers and quantifying the stresses in the dryers at EPU conditions. GE and Exelon have initiated development programs to determine the fluctuating pressure loads acting on the dryer in order to confirm the continued acceptability of operating the current dryers and for use in designing a replacement dryer that will be able to accommodate the loading during EPU operation.

Based on these needs, this evaluation was initiated to perform the comprehensive structural assessment for the replacement dryer design to assure that it could operate at EPU conditions. The loads affecting the steam dryer were determined and used as input to a three-dimensional finite element model of the Exelon replacement 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 that affect the fatigue life of the dryer. 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 and locations in the dryer. Hammer tests were performed on the assembled dryer both dry and in water with varying water elevations. Frequencies from the hammer tests compared well with the finite element model frequencies and showed that no changes were required in the model.

The replacement dryer design has incorporated several design features that reduce the likelihood of fatigue cracking [3, 4]. These features include moving welds out of high stress locations, reducing the number of fillet welds and increasing the number of full penetration welds, and allowing more flexibility in the tie bar attachments to the dryer banks. This report summarizes the dynamic, stress and fatigue analyses

performed to demonstrate that this new dryer design is structurally adequate for EPU conditions.

3. Dynamic Analysis Approach

3.1 Dynamic Loading Pressure Time Histories

The primary dynamic loads of concern on the dryer are the fluctuating pressure loads during normal operation. These pressures are the loads responsible for the fatigue damage experienced by all four of the Dresden and Quad Cities steam dryers. No direct measurements of the fluctuating pressure loads are available; therefore, two different approaches were used to define the EPU loads to be used in this analysis. One approach took pressure measurements from the water level reference legs, the steamline venturis, and steamlines (inferred from strain gauge measurements) and used these measurements in an acoustic circuit model to estimate the pressures acting on the dryer [5]. The other approach used a scale model test of the dryer, vessel and steamlines with forced air flow to simulate the pressure loads acting on the dryer [6]. The pressure measurements from the scale model were then scaled to plant conditions. The pressure measurements from these two approaches were applied as time history forcing functions to the structural finite element shell model of the dryer (Figures 3-1 and 3-2). The results from preliminary time history structural analyses showed that a high resolution pressure distribution was required in order to provide realistic results. The resolution that was required was on the same order as the mesh size of the finite element model. The acoustic circuit model could calculate this fine mesh distribution directly. The scale model test, by comparison, had a course mesh of sensors. The scale model measurements were processed through the acoustic circuit model in order to produce the fine mesh time histories required for the structural analysis. In this process, the acoustic circuit model was driven by the sensor measurements on the scale model dryer instead of the sensors on the plant steamlines.

3.2 Stress Recovery and Evaluation Methodology

The entire finite element model was divided into components with every element assigned to a component. An ANSYS macro was written to sweep thru each time step on every component to determine the time and location of the maximum stress intensity. [[

]].

ANSYS maximum stress intensity results from this macro are presented in Table 6-1. In most cases these stresses meet the GENE fatigue design criteria of 10800 psi [1, 7]. In the locations that do not meet this criteria, solid element finite element models or

handbook calculations are used to determine more accurate stresses. These high stresses occurred in locations where the shell model did not adequately represent the structure (such as trough outer support brace weld to cross beam) or had too coarse a mesh to determine the stresses (such as the trough support attachment to the support ring).

4. Material Properties

The dryer assembly was manufactured from solution heat-treated Type 316L and 304L conforming to the requirements of the material and fabrication [3]. ASME properties were used [8]. The applicable properties are shown in Table 4-1.

Table 4-1 Properties of SS304L and SS316L [Reference 8]

Material / property	Room temperature 70°F	Operating temperature 545°F
SS304L		
S_y, Yield strength, psi	25000	15940
S_u, Ultimate strength, psi	70000	57440
E, Elastic modulus, psi	28300000	25575000
SS316L		
S_y, Yield strength, psi	25000	15495
S_u, Ultimate strength, psi	70000	61600
E, Elastic modulus, psi	28300000	25575000

5. Design Criteria

5.1 Fatigue Criteria

The fatigue evaluation consists of calculating the alternating stress intensity from FIV loading at all locations in the steam dryer structure and comparing it with the allowable design fatigue threshold stress intensity. The recommended fatigue threshold stress intensities which were developed specifically for the replacement dryer are the following [7]:

1) The acceptable conservative fatigue threshold value is 10,800 psi to be used as the baseline criterion. It should be used at all critical locations that include the outer hood as the maximum acceptable value for the stress intensity amplitude.

2) The higher ASME Code Curve C value of 13,600 psi may be used in specific cases. However, its use must be technically justified.

The fatigue design criteria for the dryer is based on Figure I-9.2.2 of ASME Section III [9] which provides the fatigue threshold values for use in the evaluation of stainless steels. A key component of the fatigue alternating stress calculation at a location is the appropriate value of the stress concentration factor. The shell finite element model of the full dryer is assumed to not pick up all of the stress concentrations in the welds. Therefore, additional weld factors are applied to the maximum stress intensities recovered from the finite element time history analyses at all weld locations [10]. The stress intensities with the applied weld factors are then compared to the fatigue criteria given above.

5.2 ASME Code Criteria for Load Combinations

The ASME Code stress limits are listed in Table 5-1.

Table 5-1 ASME Code Stress Limits [9]

Service level	Stress category	Class 1 Components Stress limits (NB)	
			Stress Limit, KSI
Service levels A & B	P_m	S_m	14.4
	$P_m + P_b$	$1.5S_m$	21.6
Service level D	P_m	Min(.7Su or 2.4 Sm)	34.56
	$P_m + P_b$	1.5(Pm Allowable)	51.84

Legend:

P_m: General primary membrane stress intensity
P_b: Primary bending stress intensity
S_m: ASME Code stress intensity limit
S_U: Ultimate strength

6. Fatigue Analysis

Time history analyses were performed using ANSYS Version 8.1 [11]. The direct integration time history method was used for all of the cases described in this report. [[

]]

A Rayleigh damping of 1% was used in all of the six time history analyses. Knowing the significant frequencies that contribute to the total response is used to define the appropriate alpha and beta Rayleigh damping coefficients for the time history direct integration finite element analyses. [[

]]

6.1 Full Dryer Shell Finite Element Model

The 3D shell model of the replacement dryer is shown in Figure 6-1. The model incorporates super elements for the vane banks, submerged portion of the skirt and tie bar supports. These super elements are described in detail in sections 6.1.1 through 6.1.3. [[

]]

6.1.1 Vane Bank Super Element Model

The following components of the vane bank are modeled in the super element:

[[

]]Figures 6-11 through 6-13 show the details of the vane bank super element model.

6.1.1.1 Vane Bank Super Element Boundary Conditions

Connection to Full Dryer Model

[[

]] These super element model attachments to the full dryer finite element model are shown in Figures 6-14 and 6-15.

Internal Vane Bank Boundary Conditions

[[

]]

6.1.2 Skirt Super Element

The finite element model of the skirt is shown in Figures 6-17 and 6-18. [[

]]

6.1.3 Tie Bar Support Super Element

A solid model of the tie bar support handle was used as a super element at all tie bar support locations. This model is shown in Figure 6-16. [[

]]

6.2 Dynamic Loads

The primary dynamic loads of concern are the fluctuating pressure loads during normal operation. These are the loads responsible for the fatigue damage experienced by all four of the Dresden and Quad Cities steam dryers. No direct measurements of the fluctuating pressure loads are available; therefore, two different approaches were used to determine the loads to be used in this analysis. One approach took pressure measurements from the water level reference legs, the steamline venturis, and steamlines (inferred from strain gauge measurements) and used these measurements in an acoustic circuit model to estimate the pressures acting on the dryer [5]. The other approach used a scale model test of the dryer, vessel and steamlines to simulate the pressure loads acting on the dryer [6]. These two approaches are described with added detail in the following sections. Figures 6-19 and 6-20 show the elements in the finite element model which have fluctuating pressure applied.

6.2.1 In-Plant Loads

One of the definitions of the fluctuating pressure load used in the replacement dryer analysis was based on in-plant pressure measurements from the water level reference legs, the steamline venturis, and steamlines (inferred from strain gauge

measurements). These measurements were then used in an acoustic circuit model to estimate the pressures acting on the dryer. This load definition is referred to as the "in-plant" load case. Reference 5 describes the in-plant pressure loads used in the structural evaluation of the replacement dryer. Figure 6-21 shows the applied load at the time when the pressure is a maximum.

6.2.2 Scale Model Loads

The other definition of fluctuating pressure load used in the replacement dryer analysis was based on scale model test [[

]] The scale model test apparatus and qualification basis is described in Reference 6. The acoustic circuit model processing of the scale model pressure loads is described in Reference 13. Figure 6-22 shows the applied load at the time when the pressure is a maximum.

6.3 Frequency Content of Loads

The frequency content of the QC in-plant loads is shown in Figure 6-23. The dryer is symmetric but the loading is not. [[

]]

The frequency content of the SMT loads is shown in Figure 6-24. [[

]]

6.4 Modal Analysis

Frequency calculations were performed with the dryer supported from the RPV dryer support brackets. The support was modeled by fixing all translational degrees of freedom at the dryer support bracket interface. The entire dryer was surveyed for the component natural frequencies. However, the focus of the assessment was on the outer dryer surfaces. These calculated component natural frequencies for the skirt are shown in Figures 6-25 through 6-31. [[
]]The outer hood fundamental mode [[ ]]is shown in Figure 6-32.

6.5 Structural Response to Loads

Structural frequency response for the in-plant and SMT load cases are shown in Figures 6-33 through 6-38 for the in-plant loads and Figures 6-39 through 6-44 for the SMT loads. The in-plant loads with the +/- 10% frequency shifts allow the dryer exposure to the dominant response range based on selected dryer components. [[

]]

6.6 Stress Results from Time History Analyses

Maximum stress intensity results from ANSYS for all components of the dryer are shown in Table 6-1 [[
]]and plotted in Figures 6-52 through 6-88. [[

]]

Table 6-1 Shell Element Model Stress Intensity Summary for Time History Cases

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6.7 Weld Factors

The calculation of fatigue alternating stress using the prescribed stress concentration factors in Subsection NG is straightforward when the nominal stress is calculated using the standard strength of material formulas. However, when a finite element analysis (FEA) approach is used, the available stress component information is very detailed and requires added guidance [10] for determining a fatigue stress intensity to be used in conjunction with the Code S-N design curve. The replacement steam dryer welds are analyzed using FEA. Reference 10 provides the basis for calculating the appropriate fatigue factors for use in the S-N evaluation to assess the adequacy of these welds based on the FEA results. For the case of full penetration welds, the recommended SCF value is 1.4. In this case, the finite element stress is directly multiplied by the appropriate SCF to determine the fatigue stress. The recommended SCF is 1.8 for a fillet weld when the FEA peak stress intensity is used. Various studies have shown that the calculated fatigue stress using this alternate approach at a fillet weld correlates with that using a nominal stress and a SCF of 4.0 [14]. An alternative approach involves extracting forces and moments from the shell finite element model near the weld and calculating a nominal stress. This nominal stress would then have a factor of 4.0 applied for a fillet weld. Figure 6-89 shows a chart [[

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Table 6-2 Maximum Stress Intensity with Weld Factors

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Table 6-3 Components with High Stress Intensity and Disposition

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6.8 Disposition of High Stress Locations

Several of the components with high stress intensity are located at inner bank locations where the design fatigue limit is 13600 psi. These locations meet this fatigue limit [7]. These components are the vane cap curved part at the closure plate attachment, the inner hoods at the closure plate attachment and the trough ledge and stiffeners. [[

]] Each of these analyses is described in detail in the Section 6.9. [[

]]

6.9 Solid models and Force Extractions

In the locations where solid models were used to better characterize the stress state, forces were extracted from the full shell finite element model [[

]]

6.9.1 Mounting Blocks

The mounting block stresses [[

]] Figures 6-45 through 6-47 show the mounting block model, boundary conditions and stress results. The stresses in the mounting block are below the design fatigue allowable stress [[

]]

6.9.2 Vane Bank End Plates

The vane bank end plates in the full dryer finite element model [[

]]

[[

]] Figure 6-64 shows the model and boundary conditions. Figure 6-65

shows the maximum stress intensity on the inner bank end plate and Figure 6-66 shows the maximum stress intensity on the outer bank end plate.

Table 6-4 [[ ]]

[[

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6.9.3 Outer Trough Brace to Cross Beam Connection

A solid model of the outer trough brace to cross beam connection was created to determine weld stresses. [[

]] Forces were extracted from the shell model at the load case and time step where the highest stress occurred in this location in the shell model (Figure 6-70). The solid model is shown in Figure 6-71. Stress results are shown in Figures 6-72 and 6-73. [[

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6.9.4 Trough Support Handles

A solid model of the trough support handle was made to determine stresses in this component. The model is shown in Figure 6-48 and the stress results are shown in Figures 6-49 and 6-50. The tough handle weld stresses meet the fatigue design allowable [[ ]]

6.9.5 Trough Attachments to Support Ring

[[

]] The forces were extracted from the shell model. Figure 6-75A shows the stress intensity from the shell finite element model. The solid model is shown in Figure 6-76. Solid model stress intensity is shown in Figure 6-77 and weld stress intensity is shown in Figure 6-78. [[

]]The stress [[ ]] meets the criteria of [[ ]]. This stress is not at a weld. The adjacent weld stress has low stresses.

The stresses from the solid models are summarized in Table 6-5.

[[

Table 6-5 Stress Summary from Solid Models

]]

6.10 Fatigue Analysis Results

The fatigue analysis final results are a compilation of shell finite element model, solid model, and handbook calculations for assessing the acceptability of the steam dryer against the fatigue design criteria. [[

]] The maximum stresses directly from the ANSYS finite element analysis are summarized in Table 6-1. The stresses [[

]] are summarized in Table 6-2. The components requiring additional evaluations are summarized in Table 6-3. Table 6-4 summarized the stress results from solid models at welds (all locations identified in Table 6-2 as requiring additional evaluation are at welds). Calculations were performed on other weld locations, not given in this report, and the alternating stresses in all cases were low. The fatigue evaluation results [[

]] are summarized in Table 6-6. All components listed meet the fatigue design allowables.

Table 6-6 Fatigue Analysis Results Summary

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7. ASME Code Cases

7.1 ASME Loads and Load Combinations

The dryer is a non-safety class and Non-Seismic Category I component and performs no safety functions. The steam dryer assembly is classified as an "internal structure" per ASME Boiler and Pressure Vessel Code, Section III, Subsection NG. Therefore the steam dryer needs only to be analyzed for those faulted load combinations for which loss of structural integrity of the steam dryer could interfere with the required performance of safety class equipment (i.e., generation of loose parts that may interfere with closure of the MSIVs) or affect the core support structure integrity (shroud, top guide, core support and shroud support). However, to assure that structural integrity of the dryer is maintained over the life of the plant, the dryer was analyzed for the relevant dryer loads and load combinations for normal operation and anticipated operational occurrences (upset events) as defined in the Steam Dryer Design Specification [1]. The acceptance criteria used for these evaluations are specified in Section 5.2 and are the same as those used for safety components.

7.1.1 ASME Loads

The static and dynamic loads that are potentially acting on the steam dryer are described in this section. Section 8.1.2 describes the specific load combinations and loads used in the replacement dryer analysis.

Static Loads

Differential Pressure (DP): The operating pressure differentials across each dryer component were based on the computational fluid dynamics (CFD) analysis and reactor internal pressure differences calculated for the replacement dryer. The DP loads assumed in the analysis depend on the service condition and event being analyzed.

Deadweight (DW): Weight of the dryer components must be considered.

Thermal Expansion: 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

low alloy 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.

Dynamic Loads

Flow Induced Vibration (FIV): 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 vessel and steam piping system. Based on in-plant measurements, the acoustic pressure loading is the dominant FIV load on the dryer. The second load is turbulent buffeting caused by the steam flow through and across the dryer structure. The velocities through the dryer are low; therefore, the contribution of the buffeting load to the total FIV load is negligible.

Seismic: Seismic responses for the operating basis earthquake (OBE) and safe shutdown earthquake (SSE) 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.

Turbine Stop Valve (TSV) Loads: A turbine stop valve closure produces two loads on the dryer. The first load (TSV1) is from 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. This one-time load is applied to the area of the steamline nozzle projected onto the dryer face. The two TSV loads are separated in time and are therefore applied separately.

SRV Related Loads: The flow transient produced by rapid opening of the SRVs generates a decompression wave in the main steam line that impacts the dryer. The turbine stop valve closure acoustic load bound the relief valve pressure wave load on the dryer. Therefore, the relief valve opening decompression wave load is not explicitly included in the dryer analysis. 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. This load is considered negligible for the replacement dryer analysis because in a Mark I containment, the torus containing the suppression pool is separated from the containment structure housing the reactor vessel. This separation limits the load transmission from the torus to the steam dryer.

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.

Acoustic Pressure (AC): The flow transient produced by the break opening in the pipe generates a decompression wave in the main steam line that impacts the dryer. This load is similar in nature to the turbine stop valve closure acoustic load but acts primarily on the section of the dryer face opposite the broken steamline. A second wave will propagate in the pipe downstream from the break location (away from the RPV). This wave will eventually pass through the equalizing header and back up through the intact steamlines where it will impact the dryer. However, because of the distance the second wave must travel, these two waves are separated in time and can be addressed separately. The energy of this second wave will be dissipated through the four turbine inlet lines and the three intact steamlines; therefore, the amplitude will be significantly attenuated by the time it reaches the dryer. The loading from the second wave will be similar to the acoustic wave for the turbine stop valve case and will be bounded by that case.

Differential Pressure (DP): For large steamline breaks, the rapid vessel depressurization results in an increase in flow through the dryer. The rapid vessel depressurization also 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. The DP loading on the dryer is relatively unaffected by pipe breaks in other locations because 1) these breaks do not increase the flow through the dryer, and 2) the level swell impact on the dryer is much less severe because the vessel depressurization rate is slower or the swell starts from a much lower water level.

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. These loads are considered negligible for the replacement steam dryer analysis because in a Mark I containment, the torus containing the suppression pool is separated from the containment structure housing the reactor vessel. This separation limits the load transmission from the torus to the steam dryer.

7.1.2 ASME Load Combinations

The loads described in the preceding section were reviewed to determine the loads and load combinations to be considered in the replacement steam dryer analyses. Dresden and Quad Cities are not "New Loads" plants; 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 7-1.

Table 7-1 ASME Load Combinations

Load Case	Service Condition	Load Combination	Notes
A	Normal	DW + DPn ± FIVn	
B1	Upset	DW + DPn + TSV1 ± FIVn	
B2	Upset	DW + DPn + TSV2	1
B3	Upset	DW + DPu ± FIVu	2
B4	Upset	DW + DPn ± OBE ± FIVn	
D1A	Faulted	DW + DPn + $[SSE^2 + AC1^2]^{1/2}$ ± FIVn	3
D1B	Faulted	DW + $[DPf1^2 + SSE^2]^{1/2}$	3, 4
D2A	Faulted	DW + DPn + AC2 ± FIVn	
D2B	Faulted	DW + DPf2	4

Notes:

1. In the Upset B2 combination, FIVn is not included because the reverse flow through the steamlines will disrupt the acoustic sources that dominate the FIVn load component.
2. The relief valve opening decompression wave load (acoustic) associated with an inadvertent or stuck-open relief valve (SORV) opening is bounded by the TSV acoustic load (Upset B1); therefore, the acoustic phase of the SORV load need not be explicitly evaluated or included in the Upset load combination B3.
3. Loads from independent dynamic events are combined by the square root sum of the squares method.
4. In the Faulted D1B and D2B combinations, FIVn is not included because the level swell in the annulus between the dryer and vessel wall will disrupt the acoustic sources that dominate the FIVn load component.

AC1 = Acoustic load due to Main Steam Line Break (MSLB) outside containment, at the Rated Power and Core Flow (Hi-Power) Condition.
AC2 = Acoustic load due to Main Steam Line Break (MSLB) outside containment, at the Low Power/High Core Flow (Interlock) Condition.
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)

7.2 ASME Load Cases: Finite Element Model

The shell full dryer finite element model was modified for use in analyzing the ASME Code cases. [[

]].

7.3 ASME Load cases: Stress Results

Nominal stresses were used to calculate membrane and membrane plus bending stresses in the components for the ASME Code cases summarized in Table 7-2. Table 7-3 summarizes the design margins for the highest stresses for each service level. All dryer components meet the ASME Code stress limits for all service levels.

Table 7-2 ASME Code Cases: Stress Summary Levels A and B

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The ASME Code case results are summarized in Table 7-3.

Table 7-3 ASME Code Margins

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8. Conclusions

The fatigue evaluation of the dryer was conservatively based on two separate loading conditions; in-plant measurements and scale model test loads. Both sets of loads were run for nominal and +/-10% frequency shifts. Results of all six fluctuating pressure cases show that the replacement dryer is structurally adequate from a fatigue standpoint at EPU conditions. All locations in the steam dryer are below the design fatigue allowable stress limit as defined in the GENE Design Criteria [1]. All stresses from the ASME service level A (normal), B (upset), and D (faulted) loads are within the Code allowable limits for primary and secondary stresses. The replacement dryer is structurally adequate for EPU conditions.

9. References

[1] "Steam Dryer Design Specification (DS) 26A6266, Rev2 and Design Specification Data Sheet (DSDS) 26A6266AB, Rev.1, GENE 0000-0038-5717, Rev.0

[2] CDI: Acoustic Evaluation Modeling and Methodology.

[3] GENE Material Specification: 26A6273, rev.1.

[4] GENE Fabrication Specification: 26A6274, Rev.1.

[5] C.D.I. Technical Note No. 05-03 Rev. 1, "Quad Cities New Dryer Vulnerability Loads," April 2005

[6] GENE-0000-0032-2219-01, "Engineering Report for Quad Cities Unit 1 Scale Model Testing," April 2005.

[7] "Fatigue Stress Threshold Criteria for use in the Exelon Replacement Steam Dryer", GENE 0000-0034-8374, October 2004.

[8] ASME Code, Section II.

[9] American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, Appendix I, 1989 Edition with no Addenda

[10] "Recommended Weld Quality and Stress Concentration Factors for use in the Structural Analysis of the Exelon Replacement Steam Dryer", GENE 0000-0034-6079, February 2005.

[11] ANSYS Release 8.1, ANSYS Incorporated, 2002

[12] Test and Analysis Report Quad Cities New Design Steam Dryer Dryer #1 Experimental Modal Analysis and Correlation with Finite Element Results, LMS-Engineering Innovation, April 22, 2005

[13] C.D.I. Technical Note No. 05-04 Rev. 2, "Quad Cities New Dryer SMT Loads," April 2005

[14] "Exelon Steam Dryer Dynamic Time History Analyses,' GENE 0000-0039-3540, April 2005.

[15] "Exelon Steam Dryer Replacement Program – 2% Structural Damping for Seismic and Non-Seismic (FIV) Dynamic Analysis", Letter Report dkh0503, March 18, 2005

[16] "Quad Cities 1 & 2 Steam Dryer Replacement- 4% Structural Damping for Vane Bank FIV Analysis, GENE 0000-0039-4768, April 21, 2005.

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Figure 3-1 In-Plant Loads: Maximum Applied Pressure

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Figure 3-2 Scale Model Test Loads: Maximum Applied Pressure

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Figure 6-1 Replacement Dryer Shell Finite Element Model

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Figure 6-2 Dryer Finite Element Model Boundary Conditions

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Figure 6-3 Finite Element Model without Super Elements

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Figure 6-4 Finite Element Model: Hood Details

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Figure 6-5 Finite Element Model: Hoods

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Figure 6-6 Finite Element Model: Inner Components

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Figure 6-7 Finite Element Model: Support Ring

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Figure 6-8 Finite Element Model: Troughs

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Figure 6-9 Finite Element Model: Cross Beams

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Figure 6-10 Finite Element Model: Vane Banks

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Figure 6-11 Vane Bank Super Element

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Figure 6-12 Vane Bank Super Element

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Figure 6-13 Vane Bank Super Element : Details

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Figure 6-14 Vane Bank Super Element Attachment to Perforated Plate

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Figure 6-15 Vane Bank Super Element attachment to End Plates

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Figure 6-16 Tie Bar Handle Super Element

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Figure 6-17 Skirt Super Element

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Figure 6-18 Skirt Super Element

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Figure 6-19 Elements with Applied Pressure

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Figure 6-20 Elements with Applied Pressure]]

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Figure 6-21 In-Plant Loads at Time of Maximum Skirt Stress Intensity

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Figure 6-22 SMT Loads at Time of Maximum Skirt Stress Intensity

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Figure 6-23 QC In-plant Load Frequency Content

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Figure 6-24 SMT Load Frequency Content

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Figure 6-25 Skirt Frequency: [[ ]]

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Figure 6-26 Skirt Frequency: [[ ]]

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Figure 6-27 Skirt Frequency: [[ ]]

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Figure 6-28 Skirt Frequency: [[ ]]

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Figure 6-29 Skirt Frequency: [[ ]]

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Figure 6-30 Skirt Frequency: [[ ]]

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Figure 6-31 Skirt Frequency: [[ ]]

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Figure 6-32 Outer Hood Frequency:[[ ]]

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Figure 6-33 Frequency Response In-plant –10%: Hoods

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Figure 6-34 Frequency Response In-plant –10%: Vane Bank Ends and Tops, Skirt

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Figure 6-35 Frequency Response In-plant Nominal: Hoods

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Figure 6-36 Frequency Response In-plant Nominal: Vane Bank Ends and Tops, Skirt

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Figure 6-37 Frequency Response In-plant +10%: Hoods

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Figure 6-38 Frequency Response In-plant +10%: Vane Bank Ends and Tops, Skirt

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Figure 6-39 Frequency Response SMT -10%: Hoods

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Figure 6-40 Frequency Response SMT -10%: Vane Bank Ends and Tops, Skirt

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Figure 6-41 Frequency Response SMT Nominal: Hoods

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Figure 6-42 Frequency Response SMT Nominal: Vane Bank Ends and Tops, Skirt

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Figure 6-43 Frequency Response SMT +10%: Hoods

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Figure 6-44 Frequency Response +10%: Vane Bank Ends and Tops, Skirt

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Figure 6-45 Mounting Block Solid Model

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Figure 6-46 Mounting Block Solid Model: Boundary Conditions

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Figure 6-47 Mounting Block Solid Model: Stress Results

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Figure 6-48 Trough Support Handle Solid Model

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Figure 6-49 Trough Support Handle: Handle Stress Intensity

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Figure 6-50 Trough Support Handles: Weld Stress Intensity

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Figure 6-51 Time History Stress Intensity Results: Vane Cap Flat Portion

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Figure 6-52 Time History Stress Intensity Results: Outer Hood

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Figure 6-53 Time History Stress Intensity Results: Tie Bars

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Figure 6-54 Time History Stress Intensity Results: Frames

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Figure 6-55 Time History Stress Intensity Results: Troughs

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Figure 6-56 Time History Stress Intensity Results: Gussets

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Figure 6-57 Time History Stress Intensity Results: Vane Cap Curved Part

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Figure 6-58 Time History Stress Intensity Results: Inner Hoods

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Figure 6-59 Time History Stress Intensity Results: Closure Plates

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Figure 6-60 Time History Stress Intensity Results: T-Section Webs

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Figure 6-61 Time History Stress Intensity Results: T-Section Flanges

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Figure 6-62 Time History Stress Intensity Results: Vane Bank Inner End Plates]]

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Figure 6-63 Time History Stress Intensity Results: Vane Bank Outer End Plates

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Figure 6-64 Vane Bank End Plate Solid Model Boundary Conditions

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Figure 6-65 Vane Bank Inner End Plate Stress Intensity: 4% Damping

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Figure 6-66 Vane Bank Outer End Plate Stress Intensity: 4% Damping

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Figure 6-67 Time History Stress Intensity Results: Skirt 1% Damping

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Figure 6-68 Time History Stress Intensity Results: Skirt 2 % Damping

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Figure 6-69 Time History Stress Intensity Results: Skirt 2 % Damping, Additional Detail

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Figure 6-70 Time History Stress Intensity Results: Cross beams

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Figure 6-71 Cross Beam to Outer Trough Lower Brace Solid Finite Element Model

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Figure 6-72 Cross Beam to Outer Trough Lower Brace Stress Intensity

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Figure 6-73 Cross Beam to Outer Trough Lower Brace Weld Stress Intensity

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Figure 6-74 Cross Beam to Outer Trough Lower Brace: Linearized Stress Intensity through Weld Section

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Figure 6-75A Time History Stress Intensity Results: Support Ring

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Figure 6-75B Time History Stress Intensity Results: Support Ring

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Figure 6-76 Time History Stress Intensity Results: Trough Attachment-to-Support Ring Weld Force Extraction

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Figure 6-77 Time History Stress Intensity Results: Trough Attachment-to-Support Ring Solid Model Stresses

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Figure 6-78 Time History Stress Intensity Results: Trough Attachment-to-Support Ring Weld Solid Model Stresses

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Figure 6-79 Time History Stress Intensity Results: Trough Ledge

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Figure 6-80 Time History Stress Intensity Results: Trough Brace Gusset

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Figure 6-81 Time History Stress Intensity Results: Inner Trough Brace

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Figure 6-82 Time History Stress Intensity Results: Vertical Support Plates

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Figure 6-83 Time History Stress Intensity Results: Center Support Gussets

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Figure 6-84 Time History Stress Intensity Results: Center Plate

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Figure 6-85 Time History Stress Intensity Results: Trough End Stiffeners

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Figure 6-86 Time History Stress Intensity Results: Gusset Shoe at Cross Beams

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Figure 6-87 Time History Stress Intensity Results: Frame to Cross Beam Gussets

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Figure 6-88 Time History Stress Intensity Results: Lifting Rod Guide

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Figure 6-89: Weld Factors to use with Finite Element Results