Enclosure 2

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Quad Cities Replacement Dryer Design Uncertainties and Margins for Units 1 & 2

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Abstract

The final design flow induced vibration stresses associated with the Quad Cities Units 1 & 2 replacement steam dryers were generated using in-plant pressure measurements and a series of pressure load and structural analyses. The first step was the generation of pressure time histories created using an acoustic circuit model and main steam line pressure measurements. These pressure time histories were than applied to a finite element model of the replacement dryer to determine the fatigue stresses in the dryer. Inherent in this design process are uncertainties that are assessed in this report. These analytical uncertainties are then combined with the stress analysis results to determine the design margin for critical dryer components.

1. Introduction

This report documents the evaluation of the analytical uncertainties and design margins associated with the flow induced vibration stress qualification of the replacement steam dryers for Quad Cities (QC) Units 1 & 2. The final design stresses for the replacement steam dryers installed at QC1 and QC2 were calculated using oscillating pressure loads that were developed from an acoustic circuit model of the reactor vessel steam dome and attached steam lines. The pressure predictions from the acoustic circuit model were validated against pressures measured on the QC2 dryer surface. In the validation process, instrument measurement uncertainties and differences between measured and predicted pressures were used to determine the variability of the pressure loads calculated using this methodology. These pressure time histories were applied to a finite element model of the replacement dryer to calculate the vibration stress levels in the replacement dryer. Uncertainties inherent in the finite element model and analyses also contribute to variability in the predicted dryer stresses. Finally, the steam line and dryer measurements used to determine the dryer flow induced vibration loads were not measured at the maximum licensed thermal power of the reactor. To ensure adequate stress margin exists, the dryer flow induced vibration stresses were extrapolated to full thermal power. Uncertainties in the extrapolation process are also considered in this evaluation.

The design margins of the QC1 and QC2 replacements should be sufficient to account for these uncertainties. This report assesses these uncertainties and combines them to determine a total uncertainty, which is then conservatively applied to the predicted vibration stresses to demonstrate the replacement dryer stress levels remain below the material endurance limit.

2. Determination of Uncertainties

The Quad Cities Unit 2 replacement steam dryer was instrumented with pressure transducers to measure the oscillating pressures acting on the dryer surfaces, and strain gauges to measure actual stresses at locations adjacent to high stress areas. Pressure and strain measurements were recorded during the power ascent to measure the pressure and strain response levels as reactor power and steam flow increased. The pressure measurements were used to determine the oscillating pressure load acting on the dryer by comparing these measurements to the predictions from the acoustic circuit model. The strain measurements were used to demonstrate that dryer strain levels remain below the material endurance limit and to validate the conservatisms associated with the finite element analysis methods. The uncertainties associated with the analytical processes are determined using these dryer measurements.

The uncertainties associated with the analytical processes include the pressure time histories, the finite element model dynamic response, including frequency response and damping, and the extrapolation of the pressure loads to higher power levels. Other uncertainties are considered to be insignificant or biased to produce conservative results. For example, the peak stress intensity predictions from the finite element model are considered to be conservative when combined with the weld quality factors used to calculate the fatigue peak stress.

Based on comparisons of measured pressures to predicted pressure from the acoustic circuit model reported in Reference 3, the pressures predicted for the annular region between the dryer skirt and the reactor vessel wall are over-predicted by approximately a factor of 2. Comparisons of the measured strains to the finite element analysis strain results as presented in Reference 1, show the analytical predictions to be approximately an order of magnitude greater. The over-prediction of loads and stresses for the skirt is more than sufficient to compensate for the uncertainties in the analysis process for the skirt. Considering the magnitudes of the over-predictions for the pressure loads and the stress response, the uncertainties and stress margins for the skirt are not being addressed here. Uncertainties and stress margins for the dryer components with the smallest stress margins, not including the skirt, are assessed in this evaluation.

2.1 Pressure Load Definition Uncertainties

The bias and uncertainties associated with the acoustic circuit model used to develop the pressure time histories have been determined in Reference 3. The evaluation of the uncertainties focused on the frequency range of 135 Hz to 160 Hz. This frequency range is the primary contributor to the pressure loads and the operating stress in the replacement dryer, Reference 5. This approach was taken because considering other frequency content would tend to reduce uncertainty. Comparing pressure magnitudes based on the full 200 Hz spectrum would allow over-predictions at other frequencies to increase the predicted magnitudes making the differences between the measurements and predictions smaller. This tendency would reduce the load definition bias term.

The load definition bias and uncertainty results from Reference 3 are for the Modified 930 MWe acoustic circuit model used to develop the pressure time histories that were applied in the finite element analyses of the Quad Cities Units 1 & 2 replacement dryers. These bias and uncertainty values were based on the maximum and minimum pressure comparisons of the ACM predictions to the Quad Cities Unit 2 dryer pressure measurements. In determining the dryer response to a pressure load with very discrete frequency content, as seen in these loads, it is more important to ensure the predicted maximum and minimum pressures bound those of the measured pressures than to bound the root mean square (rms) pressure values. Matching rms values would not ensure the pressure time history would drive the dryer components to the measured peak pressures at the discrete frequencies measured. Therefore, the bias and uncertainty values determined for the peak pressures without including the skirt are used in this assessment. The bias uncertainty term of 9.10% provides the measure of the general under-prediction of the pressures and is used to increase all the pressure predictions, i.e. those that are over-predicted as well as those that are under-predicted. The uncertainty term of 5.81% represents the random variability of the predicted pressures due to measurement errors.

For Quad Cities Unit 1, pressure and strain measurements were not available on the dryer. Comparisons of the main steam line pressure measurements from Units 1 and 2 are reported in Reference 7. The steam line pressures were determined to be very similar between the two units for comparable power levels. Examination of the data comparisons clearly demonstrate the Unit 1 dryer pressure loads are generated from the same acoustic sources as Unit 2. This result is expected since the steam lines, relief valves, branch lines, and steam dome of both units are fabricated to common designs with differences limited to fabrication tolerances. The only other difference between these units that may affect the acoustic pressure sources is the two safety valves on each branch line are not always located on the same branch line. The dominant frequency of the Unit 1 sources is approximately 157.7 Hz, which is very similar to the 151 Hz and 155 Hz sources in Unit 2. The Unit 2 pressure magnitudes at these frequencies bound the Unit 1 pressure magnitudes at five of the main steam line pressure measurement locations. The three locations on Unit 1 with larger pressure measurements at these frequencies had failed strain gages, which cause pressures to be greater than they would be with all the strain measurements at those locations. The conclusion drawn from this information is that the steam line acoustic pressures from Unit 2 are the same or bound those from Unit1 for the frequencies from 150 Hz to 160 Hz for similar power levels.

The QC1 pressure time histories used for the qualification of the dryer were determined using the same acoustic circuit model that determined the pressure time histories for Unit 2, with the Unit 1 main steam line pressure measurements with the same measurement uncertainties as the Unit 2 steam line measurements. Therefore, the Unit 1 uncertainties associated with pressure load time histories are same as those applicable to Unit 2.

2.2 FEM Dynamic Response Uncertainties/Biases

The uncertainties and/or biases associated with the dynamic responses predicted by the finite element model and analyses can be assessed from the hammer test results and by comparisons of the analytical results to the dryer measurements from Quad Cities Unit 2. The uncertainties associated with the predicted responses from the finite element model have been determined for the effect of damping and the uncertainty of the model frequency.

The hammer test results presented in Reference 4 provided a comparison of the measured dynamic response of the dryer to the finite element model predicted response. It provided an assessment of these test results for the outer hoods of both the Quad Cities Unit 1 and Unit 2 replacement dryers for the [[ ]] frequency range. The result of this assessment was that the finite element model would over-predict the dynamic response of the outer hoods for this frequency range. Based on these test results, the uncertainty associated with the magnitude of the finite element model predictions is expected to be a bias toward over-prediction and therefore the uncertainty is conservatively assessed to be 0.0%.

The magnitude of the predicted responses is also affected by the damping used in the finite element analyses. Specific details of the damping used in these analyses and the technical bases are provided in Reference 6. In addition, to the bases provided in Reference 6, Reference 1 has performed a more rigorous study of the strains measured on the Unit 2 dryer to those predicted by the finite element model. This study calculated the predicted strains at the installed strain gage locations and assessed the variability of the predicted strains associated with the strain gage installation tolerances. The results of this study have demonstrated that the finite element analysis predicted results bound those measured on the dryer, therefore the damping as defined is considered to be conservative. Any reduction in the finite element analysis damping would tend to increase the predicted strains causing the over-predictions to be even larger. Consequently, the uncertainty associated with the analyzed structural damping is conservatively considered to 0.0% in this assessment.

To account for differences in the frequency content of the finite element model and the replacement dryers, additional analyses were performed using smaller time shift increments for the applied pressure time histories. This study was focusing on the discrete frequency content of the pressure loads on the dryer to ensure the predicted dryer responses included the maximum dynamic amplification of the different dryer components for the Unit 1 & Unit 2 dryers. The details and results of the study are documented in Reference 1 and have been summarized in Tables 1 and 2 for Unit 1 and Unit 2, respectively. The assessment has been limited to the dryer components with least margin and the outer hood components. Because more time step shift finite element analyses were performed for Unit 1, the time step shift uncertainty for Unit 2 is greater than the Unit 1 uncertainty.

Table 1 QC-1 FEM Dynamic Response Uncertainties Due to Time Step Shifts

QC-1 Dryer Components	Random Uncertainty
Trough	[[
Inner Hood	
Tee Section- Flange Inner Hood	
Cross Beam	
Trough- Brace Gusset	
Vane Cap Curved Part, Inner Hood	
Outer Hood	
Outer Hood-Vane Cap Curved Flat Section	
Outer Hood-Tee Section Flange	
Outer Hood-Tee Section Web	]]

Table 2 QC-2 FEM Dynamic Response Uncertainties Due to Time Step Shifts

QC-2 Dryer Component	Random Uncertainty
Trough	[[
Frame	
Tee Section- Flange Inner Hood	
Cross Beam	
Trough- Brace Gusset	
Vane Cap Curved Part, Inner Hood	
Outer Hood	
Outer Hood-Vane Cap Curved Flat Section	
Outer Hood-Tee Section Flange	
Outer Hood-Tee Section Web	]]

2.3 Dryer Stress Extrapolation Uncertainties

Since the pressure measurements used to calculate the pressure time histories were obtained at reactor thermal powers (steam flows) that were less than the maximum, the dryer component stresses were extrapolated to the maximum licensed reactor thermal power. The Quad Cities Unit 2 extrapolation was based on the pressure and strain measurements that were obtained during the power ascension of the unit. The trends for the measured pressures and strains were extrapolated from highest measured power level of 2885 MWt to the maximum licensed thermal power of 2957 MWt in Reference 2.

Power law curve fits of the measured data were used to establish an extrapolation exponent [[ ]] for the power range from 2885 MWt to 2957 MWt. The exponent was determined to bound the average exponent for both the pressure and the strain data measurements when looking at data ranges from 2480 MWt to 2885 MWt and a smaller data range of 2780 MWt to 2885 MWt. The uncertainty in this extrapolation was based on the exponent variability for the pressure data trends. The maximum exponent [[ ]] was calculated from all pressure data sets and is determined to be the uncertainty of the load extrapolation.

Based on the physical phenomena causing the acoustic pressures acting on the dryer and the trends seen from the pressures measured on the dryer, it is reasonable to assume that the magnitude of the acoustic pressures will behave as predicted by the Strouhal curve. Based on this assumption and the extrapolations presented in Reference 2, the dryer stress levels have been increased [[ ]]. The uncertainty associated with the extrapolation is determined as follows:

Load Extrapolation Uncertainty = 1 - [$(2957/2885)^{PE2}$ / $(2957/2885)^{PE1}$]

Where,

PE1 = Power exponent used to determine the extrapolation factor determined in Reference 2, [[ ]].

PE2 = Power exponent determined to be the largest from pressure data trends above 2780 MWt as determined in Reference 2, [[ ]].

The uncertainty for the Quad Cities Unit 2 stress extrapolation was determined to be 4.72%.

For extrapolation of the QC1 dryer flow induced vibration stresses, the change in dryer pressures with increasing power levels for Unit 1 was compared to those for Unit 2 in Reference 8. This study used the acoustic circuit model pressure predictions opposite the main steam line nozzles to trend the change in dryer pressures with increasing reactor power. This study focused on the pressure changes caused by the contribution of frequencies from 145 Hz to 165 Hz only and was performed for QC1 and QC2 dryer pressures. The largest extrapolation determined for Unit 1 was approximately 11%. Although this is approximately half of the extrapolation factor determined for Unit 2, the extrapolation factor and uncertainty defined for Unit 2 was applied to the margin assessment for Unit 1. It should be noted that the QC 1 extrapolation is consistent with the comparison of QC 1 and QC 2 MSL strain gage data discussed in section 2.1

2.4 Total Uncertainty

The total uncertainty for each component is determined by combining the random uncertainty terms using a square root sum of the squares (SRSS) combination method and then summing the combined random uncertainties with the bias terms. These total uncertainties are presented in Tables 3 and 4 for Quad Cities Unit 1 and Unit 2, respectively.

3. Dryer Design Margins

For this assessment, the vibration stresses for the dryer components with the least design margin were evaluated. In addition to these least margin components, the outer hood components were evaluated to demonstrate the design margin magnitude for the dryer components that have historically been most sensitive to the oscillating pressure loads.

3.1 Dryer Component Stresses

The QC1 and QC2 dryer components and stresses with least design margins were obtained from Tables 3-5 and 3-6 in Reference 1. The component stress values are the peak fatigue stresses, which include the appropriate weld quality factors based on ASME code requirements. These stress values have also been increased [[ ]] to extrapolate them to the licensed full thermal power of 2957 MWt. The QC1 and QC2 dryer components and stresses are listed in Tables 3 and 4 for QC1 and QC2, respectively.

3.2 Material Fatigue Endurance Limit

For the design margin assessment, the ASME code fatigue endurance limit for 304 stainless steel of 13.6 ksi was used as the industry accepted lower bound material endurance limit. For the outer hood components with a history of fatigue failures in the old dryer designs a reduced fatigue limit was imposed for added margin. The fatigue stresses for the outer hood components were limited to 10.8 ksi. An additional evaluation was performed using the ASME code fatigue endurance limit from the B curve of 16.5 ksi. The ASME code endurance limit from curve B is appropriate when $P_L + P_b + Q)_{range} < 27.2$ ksi. As seen in the dryer design reports, References 9 and 10, this criterion has been met for the combined normal operating and oscillating pressure loads. This additional comparison was performed to show the additional design margin when the more realistic endurance limit is used.

3.3 Dryer Component Design Margins

The dryer component design margins were calculated by increasing the peak fatigue stresses by the total uncertainty for each component. The component stress with uncertainty included was then compared to the material endurance limit to determine the design margins. These results are presented in Tables 3 and 4 for QC1 and QC2, respectively.

As seen in Table 3, the QC1 dryer components with the least design margin still satisfy the fatigue endurance limit after increasing the component stress values by the total uncertainty. The design margins for the outer hood components show significant margins to the reduced fatigue endurance limit of 10.8 ksi.

As seen in Table 4, the QC2 dryer components with the least design margin still satisfy the fatigue endurance limit after increasing the component stress values by the total uncertainty. The design margins for the outer hood components show significant margins to the reduced fatigue endurance limit of 10.8 ksi.

Table 3 QC1 Total Component Uncertainty and Design Margins

QC Unit 1	Trough	Inner Hood	Tee Section-Flange Inner Hood	Cross Beam	Trough-Brace Gusset	Vane Cap Curved Part, Inner Hood	Outer Hood	Outer Hood-Vane Cap Curved Section	Outer Hood-Tee Section Flange	Outer Hood-Tee Section Web
	Component Stress (psi)									
Component Stress (psi)	[[									]]
Uncertainties:										
Load Definition:										
Load Bias	9.10%	9.10%	9.10%	9.10%	9.10%	9.10%	9.10%	9.10%	9.10%	9.10%
Load Random	5.81%	5.81%	5.81%	5.81%	5.81%	5.81%	5.81%	5.81%	5.81%	5.81%
FEM Dynamic Response:										
-Hammer Test	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
-Time Step Shift	[[									]]
-Damping	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Load Extrapolation:	4.72%	4.72%	4.72%	4.72%	4.72%	4.72%	4.72%	4.72%	4.72%	4.72%
Total Uncertainty	**16.82%**	**16.58%**	**17.00%**	**16.58%**	**16.58%**	**16.58%**	**17.08%**	**16.58%**	**16.58%**	**16.58%**
Component Stress with Uncertainty (psi)	[[									]]
Design Endurance Limit (psi)	13600	13600	13600	13600	13600	13600	10800	10800	10800	10800
Design Margin	**3.8%**	**5.8%**	**8.0%**	**4.8%**	**0.3%**	**12.2%**	**26.4%**	**49.1%**	**65.6%**	**60.8%**
Design Margin to 16500 psi	20.7%	22.4%	24.2%	21.6%	17.8%	27.6%	51.8%	66.7%	77.5%	74.4%

Table 4 QC2 Total Component Uncertainty and Design Margins

Component Stress (psi)

QC Unit 2	Trough	Frames	Tee Section-Flange Inner Hood	Cross Beam	Trough-Brace Gusset	Outer Hood	Outer Hood-Vane Cap Curved Section	Outer Hood-Tee Section Flange	Outer Hood-Tee Section Web
Component Stress (psi)	[[								]]
Uncertainties:									
Load Definition:									
Load Bias	9.10%	9.10%	9.10%	9.10%	9.10%	9.10%	9.10%	9.10%	9.10%
Load Random	5.81%	5.81%	5.81%	5.81%	5.81%	5.81%	5.81%	5.81%	5.81%
FEM Dynamic Response:									
-Hammer Test	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
-Time Step Shift	[[								]]
-Damping	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Load Extrapolation Bias	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Load Extrapolation:	4.72%	4.72%	4.72%	4.72%	4.72%	4.72%	4.72%	4.72%	4.72%
Total Uncertainty	19.58%	19.58%	19.58%	19.58%	19.58%	19.58%	19.58%	19.58%	19.58%
Component Stress with Uncertainty (psi)	[[								]]
Design Endurance Limit (psi)	13600	13600	13600	13600	13600	13600	10800	10800	10800
Design Margin	16.3%	19.8%	26.7%	2.2%	18.3%	39.4%	46.2%	71.7%	54.6%
Design Margin to 16500 psi	31.0%	33.9%	39.6%	19.4%	32.6%	60.3%	64.8%	81.5%	70.3%

4. Conclusions

The total uncertainties associated with analysis processes used to qualify the replacement steam dryers were assessed and determined to range from 16.6% to 19.6% for both Quad Cities Units. Uncertainties associated with the determination of the pressure time histories, the finite element model dynamic responses and the extrapolation of the pressure loads to maximum licensed thermal power were assessed and included in the determination of the total uncertainty.

Using these uncertainties, the design margins for the dryer components with the least stress margins and the outer hood components were evaluated by increasing the calculated stress intensities. The results of this assessment show that the design margins for all dryer components assessed are acceptable for both units. The design margins for the Unit 1 outer hood components range from 26.4% to 65.6% margin to the design endurance limit of 10.8 ksi.

The design margins for the Unit 2 outer hood components range from 39.4% to 71.7% margin to the design endurance limit of 10.8 ksi. It should be noted in this assessment that when measured QC2 dryer strains are compared to the strains predicted by this analysis process, the predictions bound the measured results and support the results presented here.

Based on these results, it is concluded that both QC1 and QC2 replacement dryers have adequate design margins to operate at maximum licensed reactor thermal power levels.

5. References

1. GE-NE-0000-0046-5358-01-P, Quad Cities Units 1 and 2 Replacement Steam Dryer Analysis Stress, Dynamic, and Fatigue Supplementary Analyses for EPU Conditions, Revision 1, December 2005.
2. GENE-0000-0046-8129-02-P, LMS Report, Quad Cities New Design Steam Dryer Methodology for Stress Scaling Factors Based on Extrapolation from 2885 MWt to 2957 MWt of Unit #2/Dryer #1 Data, Revision 2, December 2005.
3. Exelon Report AM-2005-012, An Assessment of the Uncertainty in the Application of the Modified 930 MWe Acoustic Circuit Model Predictions for the Replacement Quad Cities Units 1 and 2 Steam Dryers, Revision 0, November 28, 2005.
4. GENE-0000-0045-9761-01-P, LMS Report Quad Cities New Design Steam Dryer - Dryer #1, Dryer #2 and Finite Element Model Outer Hood Frequency Response Functions Extension to 200 Hz, Revision 3, November 2005.
5. Exelon Report AM-2005-015, A Comparison of the Cumulative Mean Square Strain in the Application of the Modified 930 MWe Acoustic Circuit Model and FEA to the QC2 TC41 In-Vessel Test Conditions, Revision 1,
6. GE-NE-0000-0048-1485-01-P, Damping Value for Steam Dryer Hood Focused on a Single Frequency Regime, November 2005.
7. SIR-05-223, Revision 1, SIA Letter Report KKF-05-037, Comparison of Quad Cities Unit1 and Quad Cities Unit 2 Main Steam Line Strain Gage Data, July 18, 2005.
8. Continuum Dynamics, Inc. Technical Note No. 05-45, Extrapolation of QC1 and QC2 Steam Dryer Loads to 2957 MWt, December 2005.
9. GENE-0000-0043-5391-01-P, Quad Cities Unit 1 Replacement Steam Dryer Stress and Fatigue Analysis at EPU Power Level of 2957 MWt Based on Measured EPU Conditions, August 2005.
10. GENE-0000-0043-3105-01-P, Quad Cities Unit 2 Replacement Steam Dryer Stress and Fatigue Analysis Based on Measured EPU Conditions, July 2005.