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Hydrodynamic Loads on Browns Ferry Nuclear Unit 1 Steam Dryer to 200 Hz

Revision 2

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Executive Summary

Measured pressure time-history data in the four main steam lines of an SMT model of Browns Ferry Nuclear Unit 1 (BFN1) are processed by a dynamic model of the steam delivery system to predict loads on the full-scale steam dryer. These measured data are first positioned on the four main steam lines, and then used to extract acoustic sources in the system. A validated acoustic circuit methodology is used to predict the fluctuating pressures anticipated across components of the steam dryer in the reactor vessel. This pressure loading was then provided for structural analysis to assess the structural adequacy of the steam dryer in BFN1.

This effort provides BFN1 with a dryer dynamic load definition that comes directly from measured BFN1 SMT data and the application of a validated acoustic circuit methodology, at power levels where the pressure data were acquired.

Table of Contents

1. Introduction

In Spring 2005 Exelon installed new stream dryers into Quad Cities Unit 2 (QC2) and Quad Cities Unit 1. This replacement design, developed by General Electric, sought to improve dryer performance and overcome structural inadequacies identified on the original dryers, which had been in place for the last 30 years. As a means for confirming the adequacy of the steam dryer, the QC2 replacement dryer was instrumented with pressure sensors at 27 locations. These pressures formed the set of data used to validate the predictions of an acoustic circuit methodology under development by Continuum Dynamics, Inc. for several years [1]. One of the results of this benchmark exercise [2] confirmed the predictive ability of the acoustic circuit methodology for pressure loading across the dryer. This methodology, validated against the Exelon full scale data and identified as the Bounding Pressure model, is used in this effort.

This report applies this validated acoustic circuit methodology to the Browns Ferry Nuclear Unit 1 (BFN1) steam dryer and main steam line geometry. SMT data obtained from the four main steam lines and the instrumented subscale dryer were used to predict pressure levels on the SMT dryer and to generate predictions of the pressure loading on the BFN1 full-scale dryer at two power levels, Original Licensed Thermal Power (OLTP) and Extended Power Uprate (EPU).

2. Modeling Considerations

The acoustic circuit analysis of the BFN1 steam supply system is broken into two distinct analyses: a Helmholtz solution within the steam dome and an acoustic circuit analysis in the main steam lines. This section of the report highlights the two approaches taken here. These analyses are then coupled for an integrated solution.

2.1 Helmholtz Analysis

A cross-section of the steam dome (and steam dryer) is shown below in Figure 2.1, with BFN1 dimensions as shown [3]. The complex three-dimensional geometry is rendered onto a uniformly-spaced rectangular grid (with mesh spacing of approximately 1.5 inches to accommodate frequency from 0 to 200 Hz in full scale), and a solution, over the frequency range of interest, is obtained for the Helmholtz equation

$$\frac{\partial^2 P}{\partial x^2}+\frac{\partial^2 P}{\partial y^2}+\frac{\partial^2 P}{\partial z^2}+\frac{\omega^2}{a^2}P=\nabla^2 P+\frac{\omega^2}{a^2}P=0$$

where P is the pressure at a grid point, ω is frequency, and a is acoustic speed in steam.

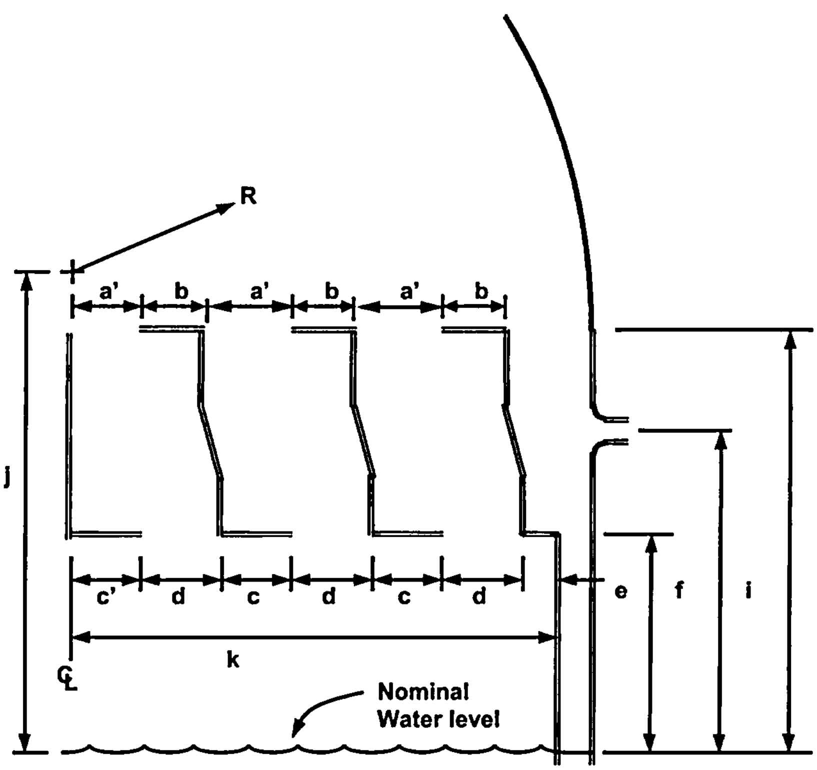

Figure 2.1. Cross-sectional description of the steam dome and dryer, with the BFN1 dimensions of a' = 16.0 in, b = 16.0 in, c' = 24.0 in, c = 14.5 in, d = 17.5 in, e = 15.5 in, f = 74.0 in, g = 163.0 in, i = 97.5 in, j = 189.0 in, k = 121.0 in, and R = 125.7 in (dimensions deduced from [3] to within 1.5 inches).

This equation is solved for incremental frequencies from 0 to 200 Hz (full scale), subject to the boundary conditions

$$\frac{dP}{dn} = 0$$

normal to all solid surfaces (the steam dome wall and interior and exterior surfaces of the dryer),

$$\frac{dP}{dn} \propto \frac{i\omega}{a} P$$

normal to the nominal water level surface, and unit pressure applied to one inlet to a main steam line and zero applied to the other three.

2.2 Acoustic Circuit Analysis

The Helmholtz solution within the steam dome is coupled to an acoustic circuit solution in the main steam lines. Pulsation in a single-phase compressible medium, where acoustic wavelengths are long compared to transverse dimensions (directions perpendicular to the primary flow directions), lend themselves to application of the acoustic circuit methodology. If the analysis is restricted to frequencies below 200 Hz, acoustic wavelengths are approximately 8 feet in length and wavelengths are therefore long compared to most components of interest, such as branch junctions.

Acoustic circuit analysis divides the main steam lines into elements which are each characterized, as sketched in Figure 2.2, by a length L, a cross-sectional area A, a fluid mean density $\bar{\rho}$, a fluid mean flow velocity $\bar{U}$, and a fluid mean acoustic speed $\bar{a}$.

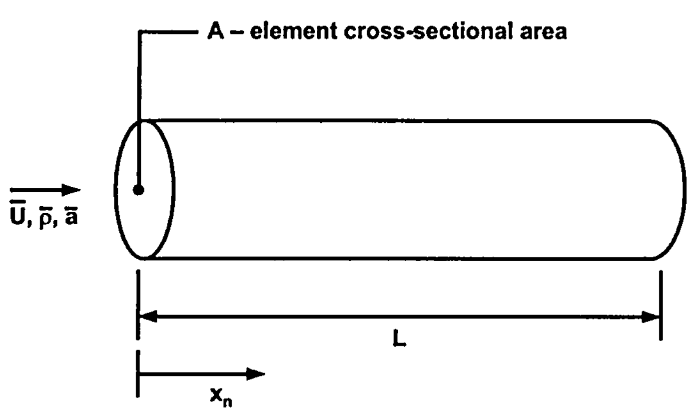

Figure 2.2. Schematic of an element in the acoustic circuit analysis, with length L and cross-sectional area A.

Application of acoustic circuit methodology generates solutions for the fluctuating pressure P_n and velocity u_n in the n^{th} element of the form

$$P_n = \left[A_n e^{ik_{1n}x_n} + B_n e^{ik_{2n}x_n}\right] e^{i\omega t}$$

$$u_n = -\frac{1}{\rho \bar{a}^2}\left[\frac{\left(\omega + \overline{U}_n k_{1n}\right)}{k_{1n}} A_n e^{ik_{1n}x_n} + \frac{\left(\omega + \overline{U}_n k_{2n}\right)}{k_{2n}} B_n e^{ik_{2n}x_n}\right] e^{i\omega t}$$

where harmonic time dependence of the form $e^{i\omega t}$ has been assumed. The wave numbers k_{1n} and k_{2n} are the two complex roots of the equation

$$k_n^2 + i\frac{f_n\left|\overline{U}_n\right|}{D_n \bar{a}^2}\left(\omega + \overline{U}_n k_n\right) - \frac{1}{\bar{a}^2}\left(\omega + \overline{U}_n k_n\right)^2 = 0$$

where f_n is the pipe friction factor for element n, D_n is the hydrodynamic diameter for element n, and $i = \sqrt{-1}$. A_n and B_n are complex constants which are a function of frequency and are determined by satisfying continuity of pressure and mass conservation at element junctions.

The solution for pressure and velocity in the main steam lines is coupled to the Helmholtz solution for the steam dome, to predict the pressure loading on the steam dryer.

The main steam line piping geometry is summarized in Table 2.1.

Table 2.1. Main steam line lengths at BFN1, scaled from SMT lengths [4]. The main steam lines are 26 inch (ID = 24.0 in).

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3. Input Pressure Data

Microphones were mounted on the four main steam lines of the SMT, and at 18 locations on the surface of the SMT dryer. Two data sets, at Original Licensed Thermal Power (OLTP) and at Extended Power Uprate (EPU), were examined.

The main steam line pressure signals may be represented in two ways, by their minimum and maximum pressure levels, and by their PSDs as a function of frequency. Table 3.1 provides the pressure level information, while Figures 3.1 to 3.8 compare the OLTP and EPU frequency content at the eight measurement locations.

Table 3.1. Main steam line (MSL) pressure levels in the SMT for BFN1 [5].

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Figure 3.1. PSD comparison of pressure measurements on the SMT main steam line A at the upper microphone: OLTP (top) and EPU (bottom).

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Figure 3.2. PSD comparison of pressure measurements on the SMT main steam line A at the lower microphone: OLTP (top) and EPU (bottom).

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Figure 3.3. PSD comparison of pressure measurements on the SMT main steam line B at the upper microphone: OLTP (top) and EPU (bottom).

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Figure 3.4. PSD comparison of pressure measurements on the SMT main steam line B at the lower microphone: OLTP (top) and EPU (bottom).

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Figure 3.5. PSD comparison of pressure measurements on the SMT main steam line C at the upper microphone: OLTP (top) and EPU (bottom).

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Figure 3.6. PSD comparison of pressure measurements on the SMT main steam line C at the lower microphone: OLTP (top) and EPU (bottom).

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Figure 3.7. PSD comparison of pressure measurements on the SMT main steam line D at the upper microphone: OLTP (top) and EPU (bottom).

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Figure 3.8. PSD comparison of pressure measurements on the SMT main steam line D at the lower microphone: OLTP (top) and EPU (bottom).

4. Results

The measured SMT main steam line pressure data were used to drive the validated acoustic circuit methodology for the BFN1 steam dome coupled to the main steam lines. Two calculations were undertaken at each power level provided.

1. A comparison was made between measured data on the subscale SMT dryer and predictions with the Bounded Pressure model [2] at subscale. These results are summarized in Figure 4.1, which illustrates the comparison between data and predictions for minimum and maximum pressures at the 18 microphone locations (identified in [6] and [7]). Note that several of the microphones are located inside the dryer (M1, M5, M8, M11, M13, and M15) and several are on the 0°-180° centerline (M6, M7, M14, and M15). Note also that the model predictions tend to match all SMT microphone data, with the exception of the 0°-180° centerline data; it appears to be least effective in comparing against SMT data here, as the main steam line sources (located at 72°, 108°, 252°, and 288°) are farthest removed from these locations. However, it should be further noted that full-scale model comparisons on the QC2 steam dryer, at the pressure sensor closest to the 0°-180° centerline (P17), shows no such under prediction [2]. It is suggested, therefore, that the SMT data may have overestimated the pressures in this region of the steam dryer, due in part to the use of a rigid steam-water boundary in SMT, and that the acoustic circuit analysis is more reasonable. Thus, no adjustment of predicted pressure at the 0°-180° region is necessary. Appendix A contains the PSD comparisons at the 18 microphones, in addition to a tabulation of the RMS comparison between predictions and measurements.

2. A prediction was made at full scale on the BFN1 dryer based on the scaling factors identified by GE [4, 5] and summarized in Table 4.1. A low resolution load, developed at the nodal locations identified in Figures 4.2 to 4.5, produces the maximum differential and RMS pressure levels across the dryer as shown in Figure 4.6. Since the highest loads are predicted on the surfaces of the outer bank hoods (and not on their edges), two sets of additional plots are shown in Figures 4.7 and 4.8 for the peak loads.

Table 4.1. Scaling factors used in converting SMT data to full scale.

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Figure 4.1. Maximum pressures measured and predicted at the 18 microphones on the SMT of the BFN1 dryer. Note the close agreement at microphones M2 and M3, and M9 and M10, on the outside of the outer bank hoods opposite the main steam lines. The closed circles denote microphones positioned on the inside of the dryer, while the open circles denote microphones positioned along the 0°-180° dryer centerline.

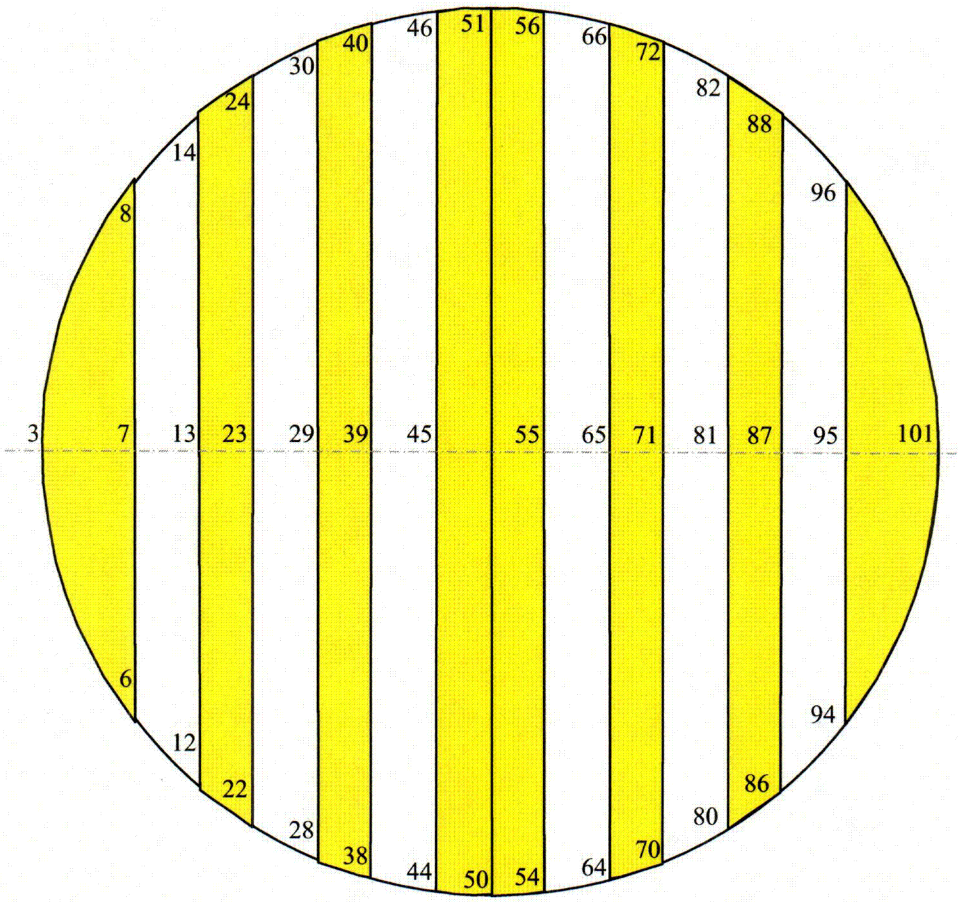


Figure 4.2. Bottom plates pressure node locations (low resolution), with pressures acting downward in the notation defined here.

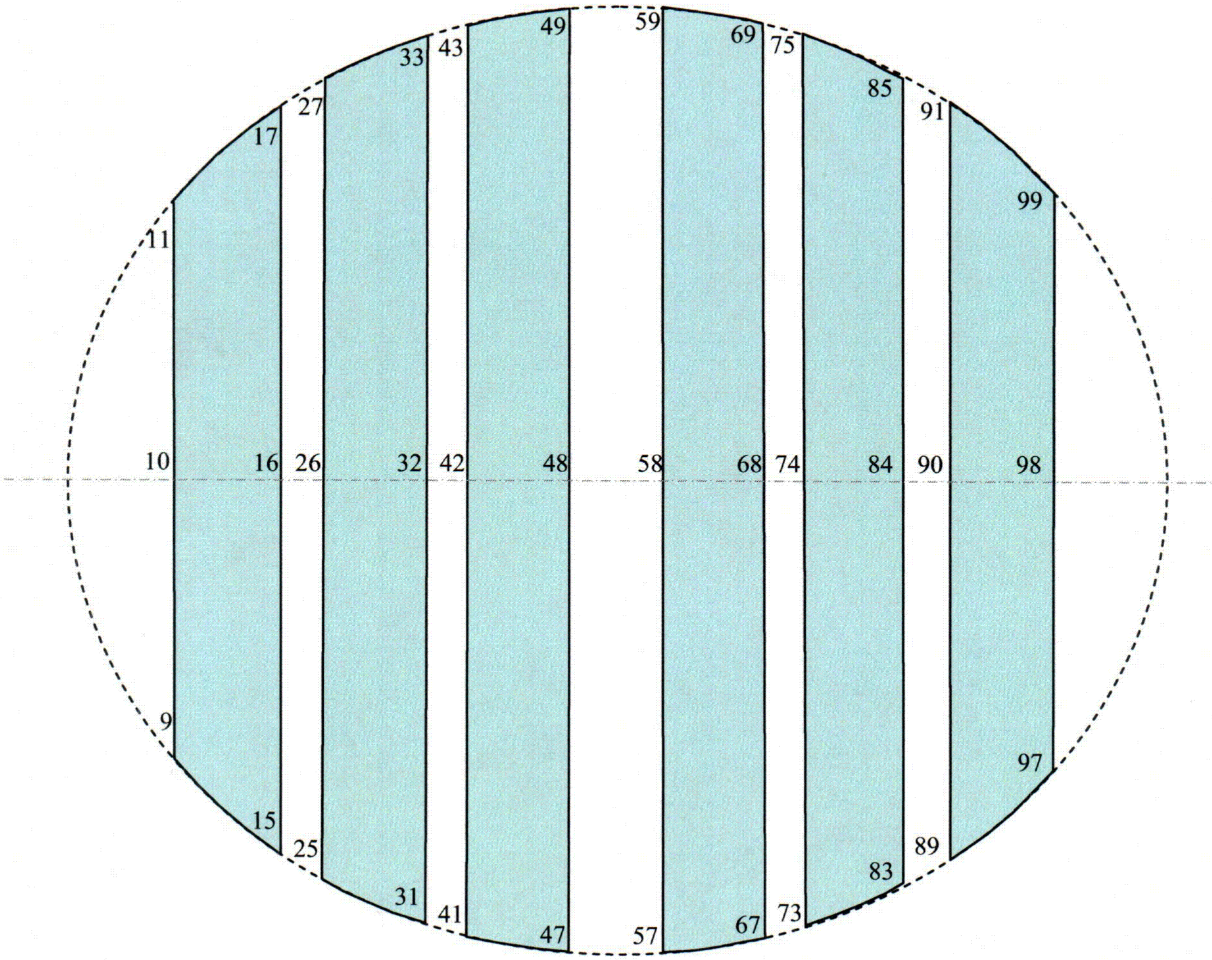


Figure 4.3.Top plates pressure node locations (low resolution), with pressures acting downward in the notation defined here.

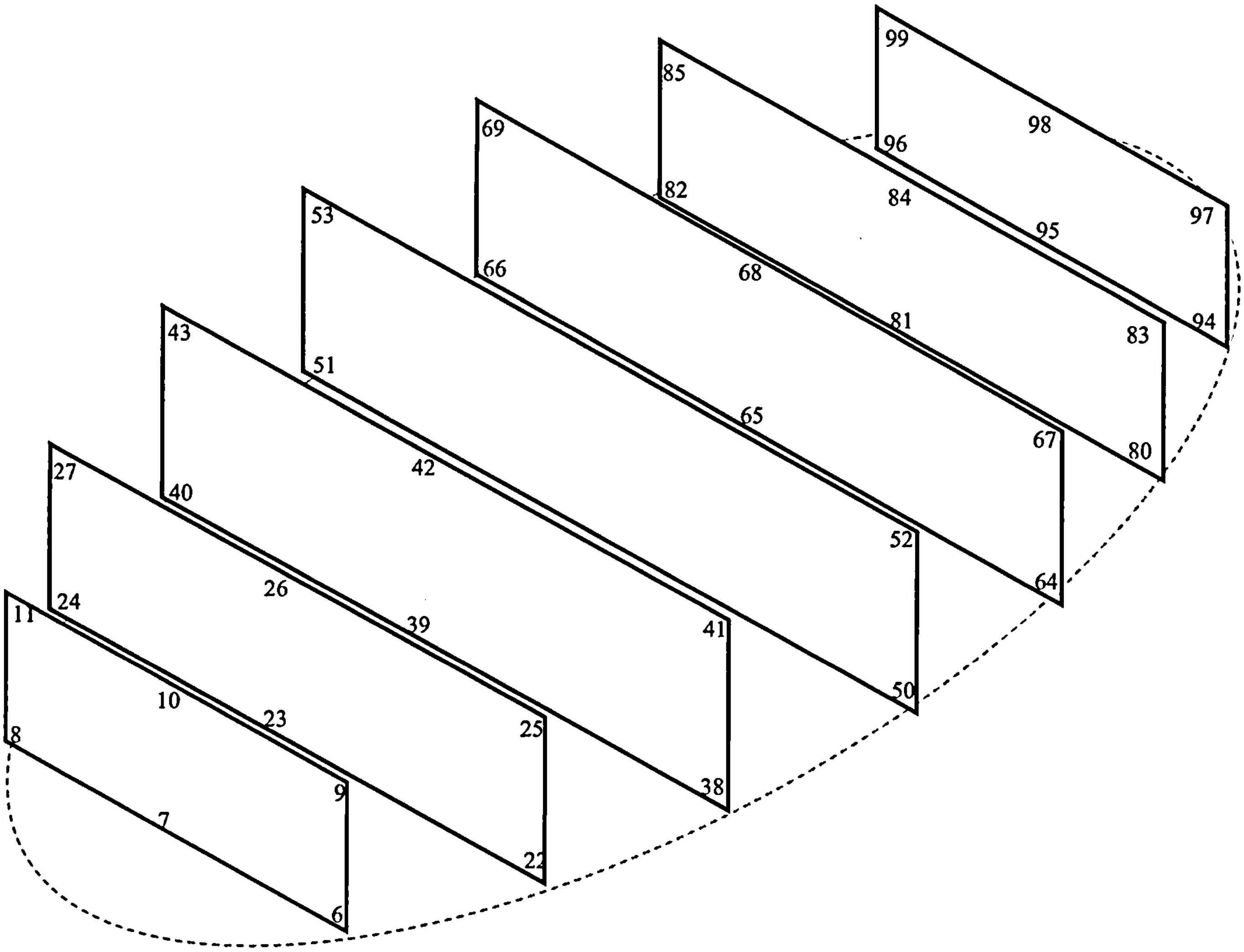


Figure 4.4. Vertical plates: Pressures acting left to right on panels 6-11, 22-27, 38-43, and 50-54; acting right to left on panels 64-69, 80-85, and 94-99 (low resolution).

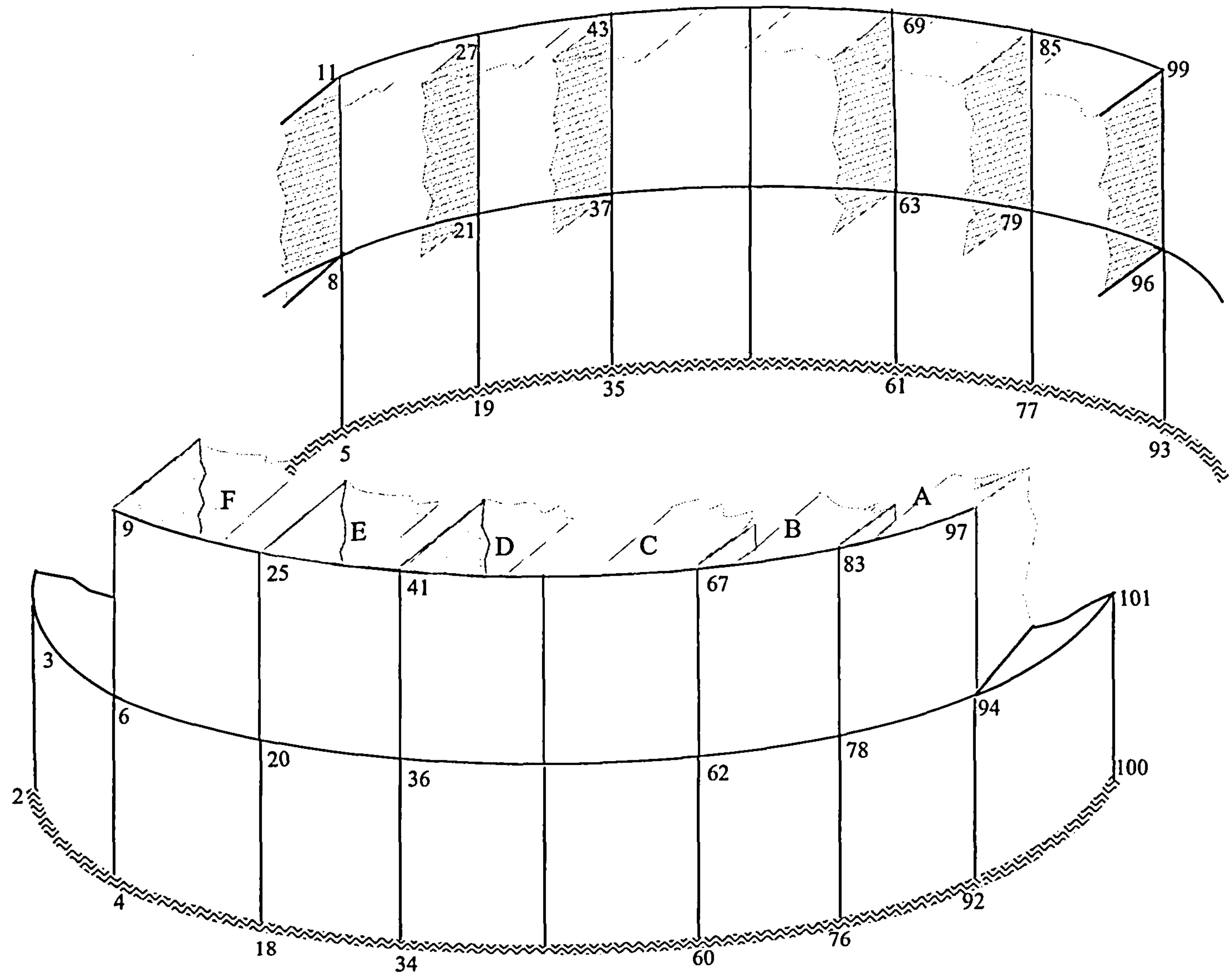


Figure 4.5. Skirt plates: Pressure acting outward on the outer dryer 0°/180° surfaces and the skirt (low resolution).

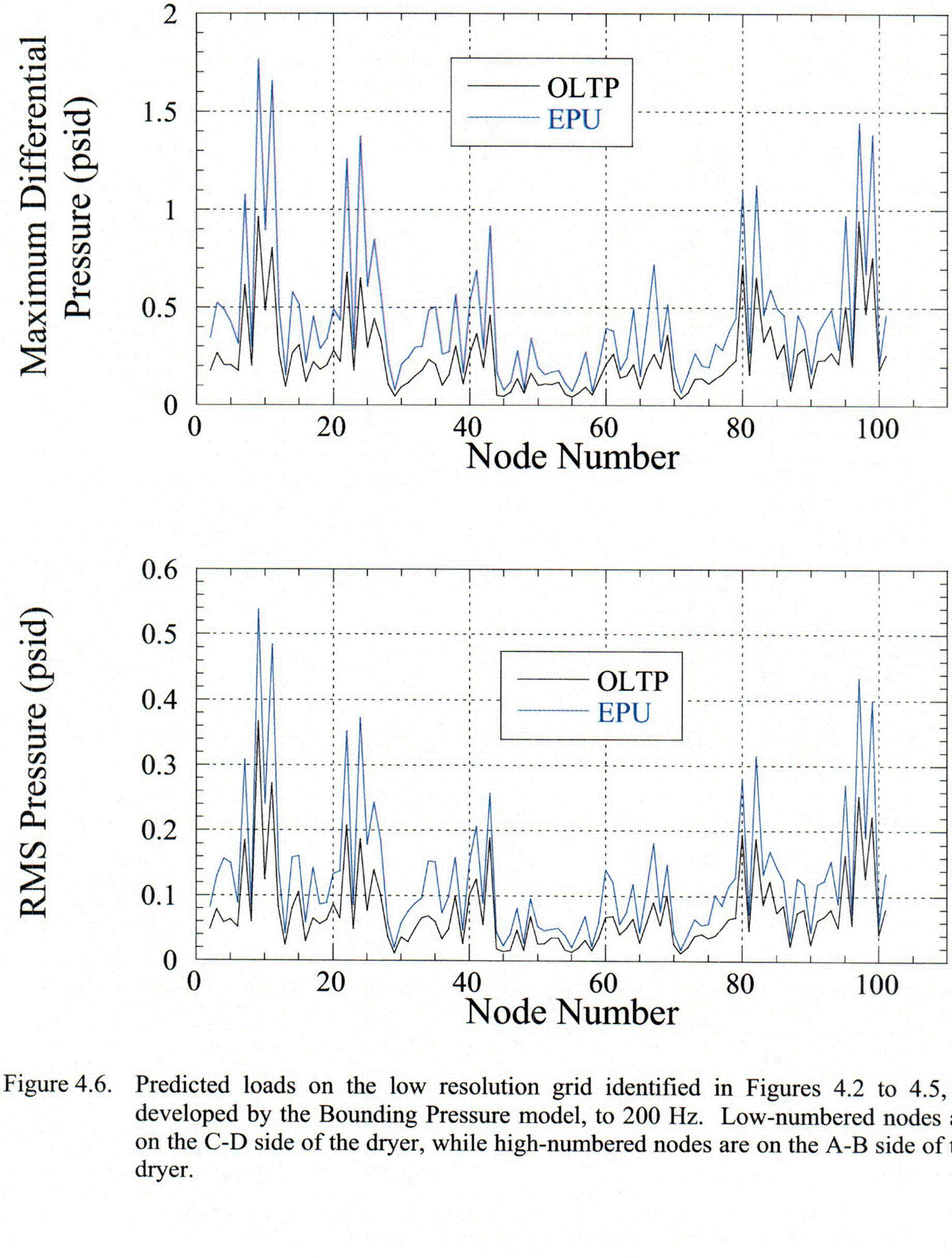
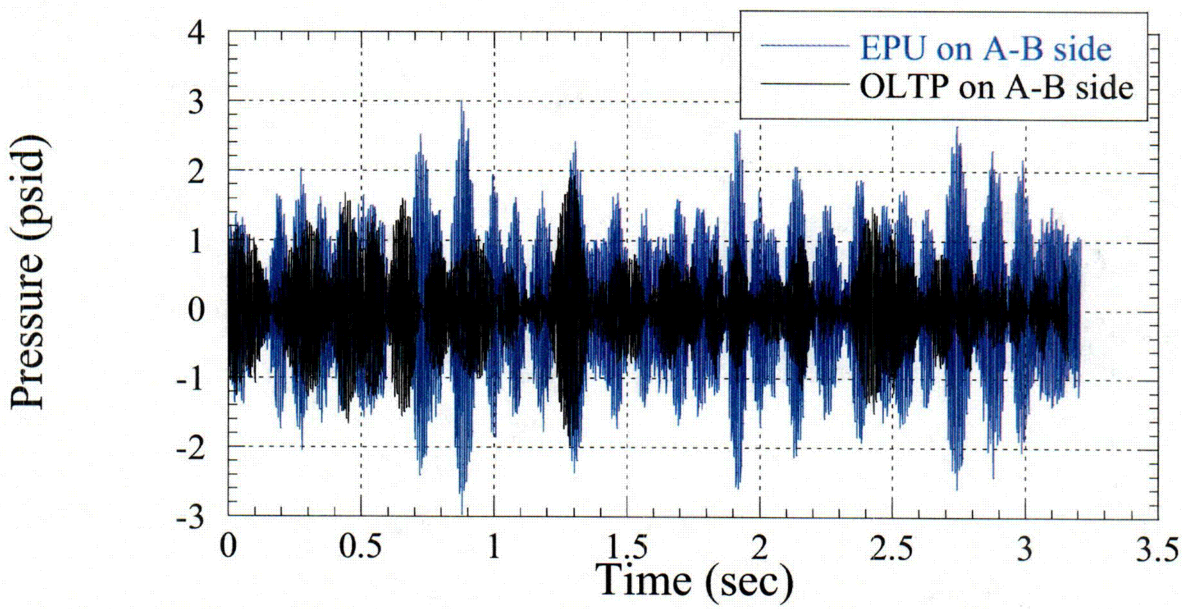


Figure 4.6. Predicted loads on the low resolution grid identified in Figures 4.2 to 4.5, as developed by the Bounding Pressure model, to 200 Hz. Low-numbered nodes are on the C-D side of the dryer, while high-numbered nodes are on the A-B side of the dryer.



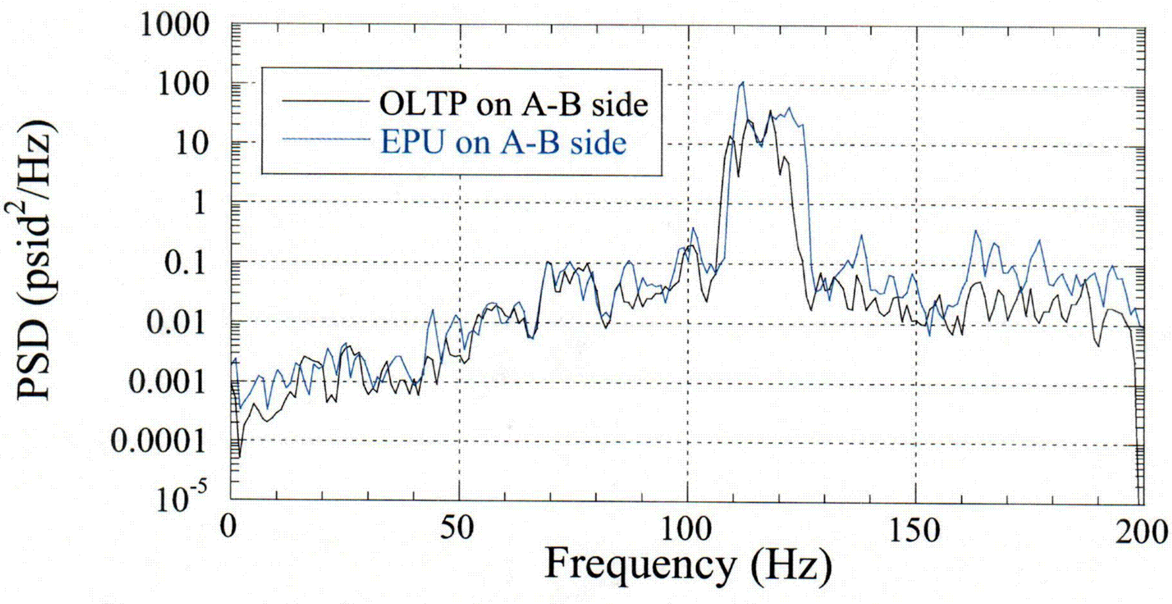


Figure 4.7. Time history and PSD of the maximum high-resolution pressure loads predicted on the A-B side of the BFN1 steam dryer at full scale. The behavior of the PSDs shown here, specifically below 125 Hz, is dependent on the conversion factors summarized in Table 4.1.

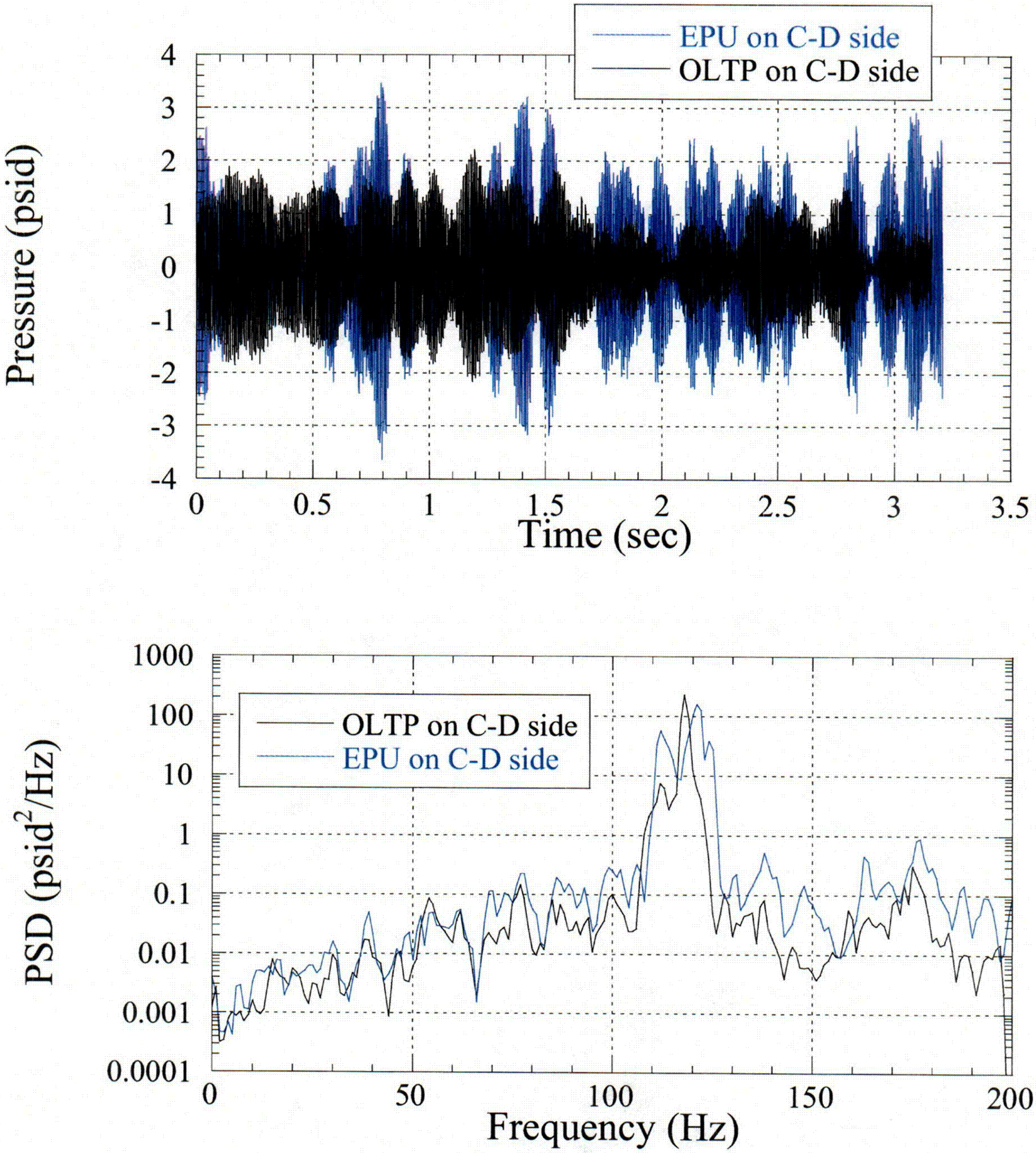


Figure 4.8. Time history and PSD of the maximum high-resolution pressure loads predicted on the C-D side of the BFN1 steam dryer at full scale. The behavior of the PSDs shown here, specifically below 125 Hz, is dependent on the conversion factors summarized in Table 4.1.

5. Uncertainty Analysis

The analysis of potential uncertainty occurring at BFN1 consists of several contributions, including the following: the uncertainty from using SMT data, the uncertainty from collecting data on the main steam lines at locations other than the locations on Quad Cities Unit 2 (QC2), and the uncertainty in the Bounding Pressure model.

1. An uncertainty analysis of the SMT facility should be provided by GE.

2. Quad Cities Unit 2 dryer data at OLTP conditions were used to generate an uncertainty analysis of the Acoustic Circuit Methodology (ACM) [2] for BFN1.

The analysis follows the analysis previously undertaken for Vermont Yankee [8]. Typically, three to five PSD maximums are present between 148.9 Hz and 156.1 Hz, depending on the pressure sensor examined. Each peak is integrated from trough to trough and combined with the other peaks. The RMS pressure is found by taking the square root of this sum.

The fifteen pressure sensor locations on the outer bank hood (P1 to P12 opposite main steam lines A and D, and P18, P20, and P21 opposite main steam lines C and D) are compared in this analysis. Table 5.1 summarizes the RMS pressures.

Table 5.1. Measured and predicted RMS pressures at the specified pressure sensor locations on the Quad Cities Unit 2 dryer.

Location	Measured P_{RMS} (psid)	Predicted P_{RMS} (psid)
P1	0.1243	0.1232
P2	0.1453	0.1694
P3	0.1444	0.2227
P4	0.0846	0.0638
P5	0.0881	0.0588
P6	0.1170	0.1254
P7	0.1069	0.1093
P8	0.1507	0.1517
P9	0.1567	0.1613
P10	0.1051	0.1060
P11	0.1249	0.1134
P12	0.2064	0.1844
P18	0.1715	0.2627
P20	0.1827	0.3627
P21	0.3354	0.3509

Rev 2

The predicted and measured data can be compared to characterize bias as well as a nominal uncertainty.

The bias is computed by taking the difference between the measured and predicted values at each point and dividing the mean of the differences by the mean of the measured data.

The ACM individual point uncertainty is defined in this analysis as the fraction computed by the expression

$(P_{meas}/P_{pred}) - 1.0$

where P_{meas} is the measured pressure and P_{pred} is the predicted pressure. Negative numbers imply that the predictions are conservative. The standard deviation of the ACM individual point uncertainties can be computed to provide an average ACM uncertainty. This uncertainty can be combined with other random uncertainties, typically by SRSS methods, to determine an overall uncertainty. The overall uncertainty is then combined algebraically with any bias terms that exist to determine a total uncertainty factor to be applied.

With the data found in Table 5.1, the ACM bias and uncertainty standard deviation (in percentage) can be computed, and are shown in Table 5.2.

Table 5.2. Uncertainty when comparing P_{RMS} values from Table 5.1.

ACM Bias (%)	-14.3 (conservative)
Standard Deviation of Point ACM Uncertainty (%)	24.5

Rev 2

These results can then be combined with statistics obtained from data collection at the plant. Tables 5.3 and 5.4 summarize the various uncertainties that should be considered, following the guidelines suggested for the Quad Cities Unit 2 plant [9], for the plant and the SMT data, respectively.

Table 5.3. Bias and uncertainty contributions to total uncertainty for BFN1 plant data.

Uncertainty Term	Absolute Effect (%)	Effect on Bias	Effect on Uncertainty
Pressure Measurement	5.38%		±5.38%
Pressure Sensor Location Uncertainty	Placement identical to QC2 strain gages		0%
ACM Low Frequency Limitations		3% bias on peak-to-peak pressure for 0 to 20 Hz [9]	
Pressure Sensor Measurement	3.9% Absolute ** 2.9% Relative **		±2.9% **
Pressure Sensor Phenomenological	N/A	-3% to -8% bias on sensor reading **	
Structural FEA			Bounding values selected based on ±10% time step sensitivity cases
ACM Bias and Uncertainty		-14.3%	24.5%
NET EFFECT		-14.3% net bias	25.3% SRSS of measurement errors: TOTAL = 11.0%

** denotes QC2 values

Rev 2

Table 5.4. Bias and uncertainty contributions to total uncertainty for BFN1 SMT data.

Uncertainty Term	Absolute Effect (%)	Effect on Bias	Effect on Uncertainty
Microphone Measurement	*		*
Microphone Location Uncertainty			6.7%
ACM Low Frequency Limitations		3% bias on peak-to-peak pressure for 0 to 20 Hz [9]	
Pressure Sensor Measurement	3.9% Absolute ** 2.9% Relative **		±2.9% **
Pressure Sensor Phenomenological	N/A	-3% to -8% bias on sensor reading **	
Structural FEA			Bounding values selected based on ±10% time step sensitivity cases
ACM Bias and Uncertainty		-14.3%	24.5%
NET EFFECT		-14.3% net bias	25.6% SRSS of measurement errors: TOTAL = 11.3%

** denotes QC2 values
* denotes values to be included in SMT uncertainty

Rev 2

6. Conclusions

The C.D.I. acoustic circuit analysis, using SMT measured data for BFN1:

a) Determines that steam dryer maximum differential pressure loads, based on the validated Bounding Pressure model, are about 2.2 psid (OLTP) and 3.6 psid (EPU), after converting subscale predictions to full scale.

b) Predicts that the loads on dryer components are largest for components nearest the main steam line inlets and decrease inward into the reactor vessel.

c) Determines that the validated Bounding Pressure model predicted pressures agree well with SMT data on the subscale dryer, with the exception being along the 0°-180° centerline, where the SMT data are believed to be conservative. This discrepancy is greatest on the skirt along the 0°-180° centerline and results from the fact that the acoustic circuit methodology incorporates acoustic radiation into the water between the skirt and the vessel. The acoustic circuit methodology predicts the QC2 skirt data conservatively and therefore it is believed that the SMT data is conservative on the skirt.

The following additional work is suggested:

- It is highly recommended that strain gages or pressure transducers be positioned at distances similar to those in Quad Cities Unit 2 (9.5 and 41.0 feet from the inside of the steam dome [2]), and that full scale data be collected and analyzed.

7. References

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Appendix A: SMT Dryer Comparisons

This appendix contains the comparisons between model predictions and pressure measurements on the SMT dryer, for both OLTP and EPU conditions. A comparison of RMS levels is given in Table A.1.

Table A.1. Summary of RMS pressures at the two power levels examined.

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Figure A.1. PSD comparisons between SMT data for Browns Ferry and ACM predictions, for microphone M1 on the inside of the outer bank hood opposite main steam line C: OLTP (top) and EPU (bottom).

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Figure A.2. PSD comparisons between SMT data for Browns Ferry and ACM predictions, for microphone M2 on the outside of the outer bank hood opposite main steam line C: OLTP (top) and EPU (bottom).

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Figure A.3. PSD comparisons between SMT data for Browns Ferry and ACM predictions, for microphone M3 on the outside of the outer bank hood opposite main steam line D: OLTP (top) and EPU (bottom).

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Figure A.4. PSD comparisons between SMT data for Browns Ferry and ACM predictions, for microphone M4 on the outside of the skirt between main steam lines C and D: OLTP (top) and EPU (bottom).

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Figure A.5. PSD comparisons between SMT data for Browns Ferry and ACM predictions, for microphone M5 on the inside of the skirt between main steam lines C and D: OLTP (top) and EPU (bottom).

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Figure A.6. PSD comparisons between SMT data for Browns Ferry and ACM predictions, for microphone M6 on the outside of the hood wall between main steam lines B and C: OLTP (top) and EPU (bottom).

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Figure A.7. PSD comparisons between SMT data for Browns Ferry and ACM predictions, for microphone M7 on the outside of the skirt wall between main steam lines B and C: OLTP (top) and EPU (bottom).

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Figure A.8. PSD comparisons between SMT data for Browns Ferry and ACM predictions, for microphone M8 on the inside of the skirt wall between main steam lines B and C: OLTP (top) and EPU (bottom).

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Figure A.9. PSD comparisons between SMT data for Browns Ferry and ACM predictions, for microphone M9 on the outside of the outer bank hood opposite main steam line B: OLTP (top) and EPU (bottom).

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Figure A.10. PSD comparisons between SMT data for Browns Ferry and ACM predictions, for microphone M10 on the outside of the outer bank hood opposite main steam line A: OLTP (top) and EPU (bottom).

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Figure A.11. PSD comparisons between SMT data for Browns Ferry and ACM predictions, for microphone M11 on the inside of the outer bank hood opposite main steam line A: OLTP (top) and EPU (bottom).

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Figure A.12. PSD comparisons between SMT data for Browns Ferry and ACM predictions, for microphone M12 on the outside of the skirt between main steam lines A and B: OLTP (top) and EPU (bottom).

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Figure A.13. PSD comparisons between SMT data for Browns Ferry and ACM predictions, for microphone M13 on the inside of the skirt between main steam lines A and B: OLTP (top) and EPU (bottom).

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Figure A.14. PSD comparisons between SMT data for Browns Ferry and ACM predictions, for microphone M14 on the outside of the hood between main steam lines A and D: OLTP (top) and EPU (bottom).

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Figure A.15. PSD comparisons between SMT data for Browns Ferry and ACM predictions, for microphone M15 on the outside of the skirt between main steam lines A and D: OLTP (top) and EPU (bottom).

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Figure A.16. PSD comparisons between SMT data for Browns Ferry and ACM predictions, for microphone M16 on the inside of the skirt between main steam lines A and D: OLTP (top) and EPU (bottom).

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Figure A.17. PSD comparisons between SMT data for Browns Ferry and ACM predictions, for microphone M17 on the outside of the second bank hood opposite main steam line B: OLTP (top) and EPU (bottom).

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Figure A.18. PSD comparisons between SMT data for Browns Ferry and ACM predictions, for microphone M18 on the outside of the third bank hood opposite main steam line B: OLTP (top) and EPU (bottom).