ATTACHMENT 5

CDI REPORT NO. 10-10NP, "ACOUSTIC AND LOW FREQUENCY HYDRODYNAMIC LOADS AT CLTP POWER LEVEL ON NINE MILE POINT UNIT 2 STEAM DRYER TO 250 HZ USING ACM REV. 4.1," REV. 1 (NON-PROPRIETARY)

Nine Mile Point Nuclear Station, LLC
June 30, 2010

C.D.I. Report No. 10-10NP

Acoustic and Low Frequency Hydrodynamic Loads at CLTP Power Level on Nine Mile Point Unit 2 Steam Dryer to 250 Hz Using ACM Rev. 4.1

Revision 1

Prepared by

Continuum Dynamics, Inc.
34 Lexington Avenue
Ewing, NJ 08618

Prepared under Purchase Order No. 7708631 for

Constellation Energy Group
Nine Mile Point Nuclear Station, LLC
P. O. Box 63
Lycoming, NY 13093

Prepared by

Milton E. Teske

Approved by

Alan J. Bilanin

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Executive Summary

Measured strain gage time-history data in the four main steam lines at Nine Mile Point Unit 2 were processed by a dynamic model of the steam delivery system to predict loads on the full-scale steam dryer. These measured data were first converted to pressures, then positioned on the four main steam lines and used to extract acoustic sources in the system. A validated acoustic circuit methodology was used to predict the fluctuating pressures anticipated across components of the steam dryer in the reactor vessel. The acoustic circuit methodology included a low frequency hydrodynamic contribution, in addition to an acoustic contribution at all frequencies. This pressure loading was then provided for structural analysis to assess the structural adequacy of the steam dryer in Nine Mile Point Unit 2.

This effort provides the Constellation Energy Group with a dryer dynamic load definition that comes directly from measured Nine Mile Point Unit 2 full-scale data and the application of a validated acoustic circuit methodology, at a power level where data were acquired.

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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. (C.D.I.) 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, with the inclusion of a low frequency hydrodynamic load. This approach, validated against the Exelon full-scale data and recently improved and identified as the Acoustic Circuit Model (ACM) Rev. 4.1 [3], is used in the effort discussed herein.

ACM Rev. 4.1 filters the QC2 data in exactly the same way as the NMP data, that is, (1) the EMF frequencies of 60, 120, 180, and 240 Hz are filtered; (2) the vane passing frequency and other non-acoustic frequencies identified in the EIC data are also filtered; and (3) the strain gage signals at the upper and lower locations on each main steam line are coherence filtered. The resulting loads are computed for the Nine Mile Point dryer, after applying bias and uncertainty values found when comparing model predictions on the QC2 dryer with pressure data recorded on the outer bank hoods of the QC2 dryer.

This report applies this validated methodology to the Nine Mile Point Unit 2 (NMP2) steam dryer and main steam line geometry. Strain gage data obtained from the four main steam lines were used to predict pressure levels on the NMP2 full-scale dryer at Current Licensed Thermal Power (CLTP). These data were then used to predict dryer stresses, and to determine the minimum stress margin on the dryer. This result will then be used to develop limit curves.

2. Modeling Considerations

The acoustic circuit analysis of the NMP2 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 NMP2 dimensions as shown [4]. 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 250 Hz in full scale), and a solution, over the frequency range of interest, is obtained for the Helmholtz equation

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

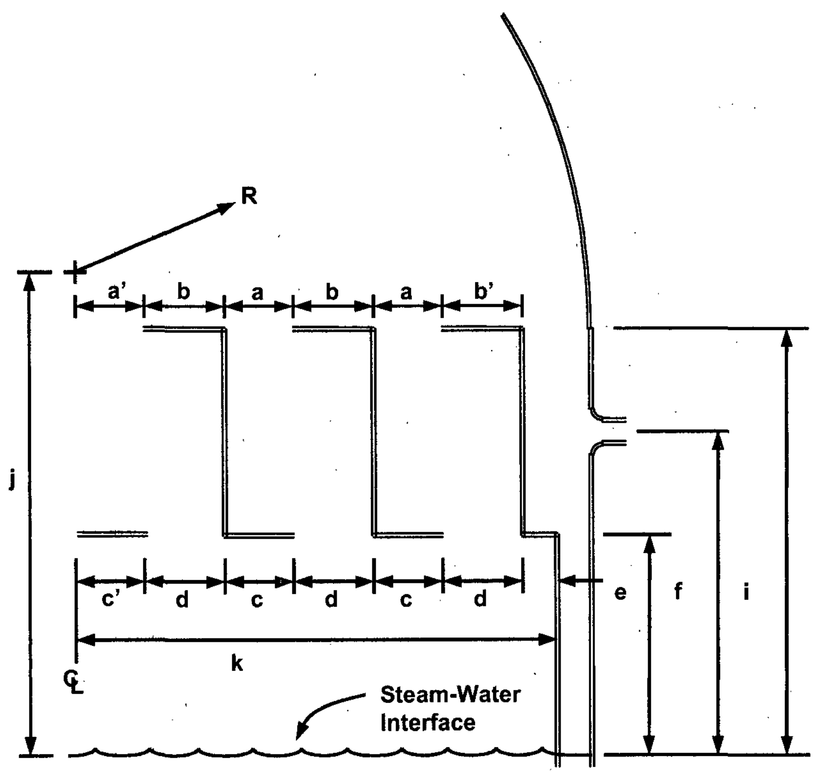

Figure 2.1. Cross-sectional description of the steam dome and dryer at NMP2, with the dimensions of a = 18.25 in, a' = 15.25 in, b = 13.27 in, b' = 13.65 in, c = 15.75 in, c' = 24.0 in, d = 15.75 in, e = 16.25 in, f = 71.5 in, g = 160.625 in, i = 84.5 in, j = 181.5 in, k = 118.75 in, and R = 124.75 in.

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

This equation is solved for incremental frequencies from 0 to 250 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 250 Hz, acoustic wavelengths are approximately eight 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 $\bar{a}$.

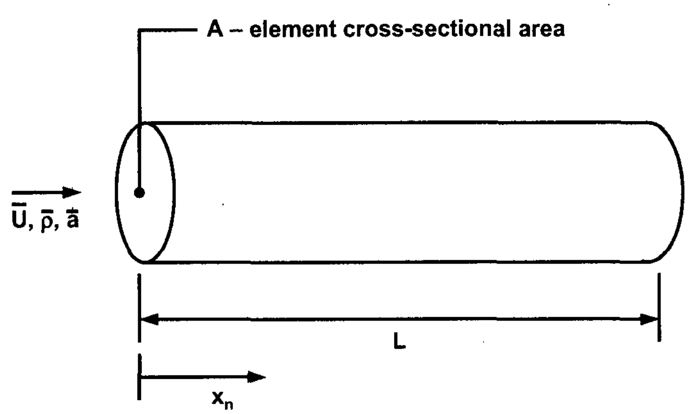

Figure 2.2. Schematic of an element in the acoustic circuit analysis, with length L and cross-sectional area A.

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

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

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

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

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

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 in 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 NMP2, measured from the inside wall of the steam dome down the centerline of the main steam lines. Main steam line diameter is 26 inch Schedule 80 (ID = 23.50 in).

Main Steam Line	Length to First Strain Gage Measurement (ft)	Length to Second Strain Gage Measurement (ft)
A	13.6	26.2
B	14.5	19.9
C	22.1	27.5
D	20.4	25.8

2.3 Low Frequency Contribution

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3. Input Pressure Data

Strain gages were mounted on the four main steam lines of NMP2. Three data sets were examined in this analysis. The first dataset recorded the strain at Low Power, the second dataset recorded the strain at Current Licensed Thermal Power (100% power level or CLTP), and the third data set recorded the strain at near-zero voltage on the strain gages (EIC noise at CLTP). The data were provided in the following files:

Data File Name	Power Level	Voltage
20100503205447	21%	10.0 V
20100506111925	100%	10.0 V
20100506112240	100%	0.01 V (EIC)

The strain gage signals were converted to pressures by the use of the conversion factors provided in [5] and summarized in Table 3.1. The raw data signals are shown in Figure 3.1. Exclusion frequencies were identified in the EIC data and used to remove extraneous signals, as also identified in [5], summarized in Table 3.2 and shown in Figure 3.2. Note that EIC data were not subtracted from the corresponding CLTP data. CLTP signals were further processed by coherence filtering as described in [3]. Coherence between the upper and lower signals on each main steam line is shown in Figure 3.3.

The filtered main steam line pressure signals may be represented in two ways, by their minimum and maximum pressure levels, and by their PSDs. Table 3.3 provides the pressure level information, while Figure 3.4 compares the CLTP frequency content at the eight strain gage locations.

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Table 3.1. Conversion factors from strain to pressure [5]. Channels are averaged to give the average strain.

	Strain to Pressure (psid/μstrain)	Channel Number	Channel Number	Channel Number	Channel Number
MSL A Upper	3.82	1	2	3	4
MSL A Lower	3.84	5	6	7	8
MSL B Upper	3.84	9	10	11	12
MSL B Lower	3.81	13	14	15	16
MSL C Upper	3.85	17	18	19	20
MSL C Lower	3.81	21	22	23	24
MSL D Upper	3.92	25	26	27	28
MSL D Lower	3.94	29	30	31	32

Table 3.2. Exclusion frequencies for NMP2 strain gage data, as suggested in [5]. The frequency range is applied with a second-order, stop-band Butterworth filter in MatLab.

Frequency Range (Hz)	Exclusion Cause
0.0 – 2.0	Mean
59.85 – 60.15	EMF Frequency
119.85 – 120.15	EMF Frequency
179.85 – 180.15	EMF Frequency
239.85 – 240.15	EMF Frequency
149.0 – 149.4	Recirculation Vane Passing Frequency: 100%
84.0 – 84.5	Non-Coherent Electrical Source

Table 3.3. Main steam line (MSL) pressure levels in NMP2 at CLTP conditions, after coherence filtering.

	Minimum Pressure (psid)	Maximum Pressure (psid)	RMS Pressure (psid)
MSL A Upper	-1.92	1.72	0.41
MSL A Lower	-1.74	1.86	0.44
MSL B Upper	-1.37	1.60	0.33
MSL B Lower	-1.72	1.92	0.42
MSL C Upper	-1.91	1.93	0.45
MSL C Lower	-1.97	2.38	0.48
MSL D Upper	-1.53	1.33	0.34
MSL D Lower	-2.03	1.87	0.46

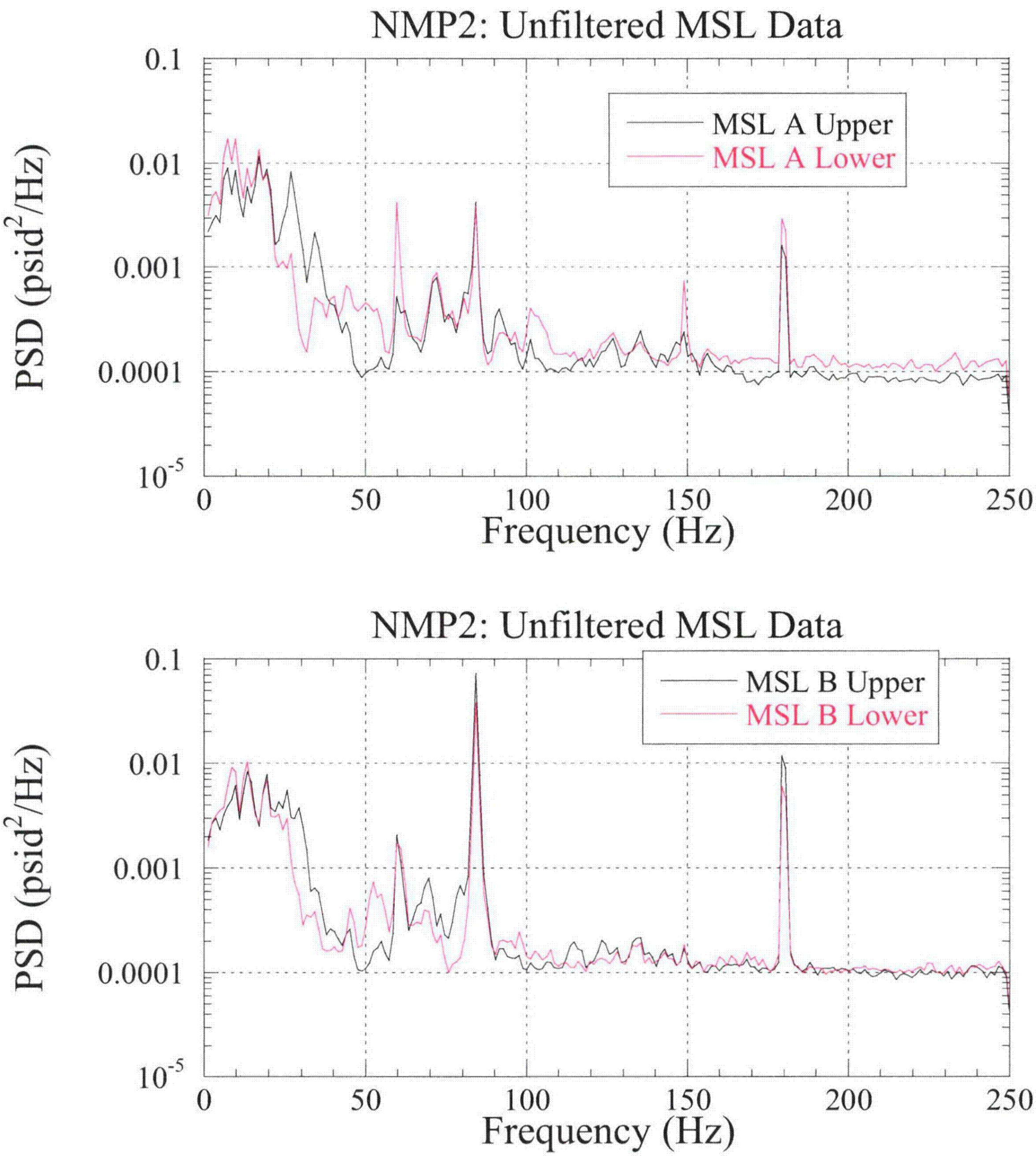
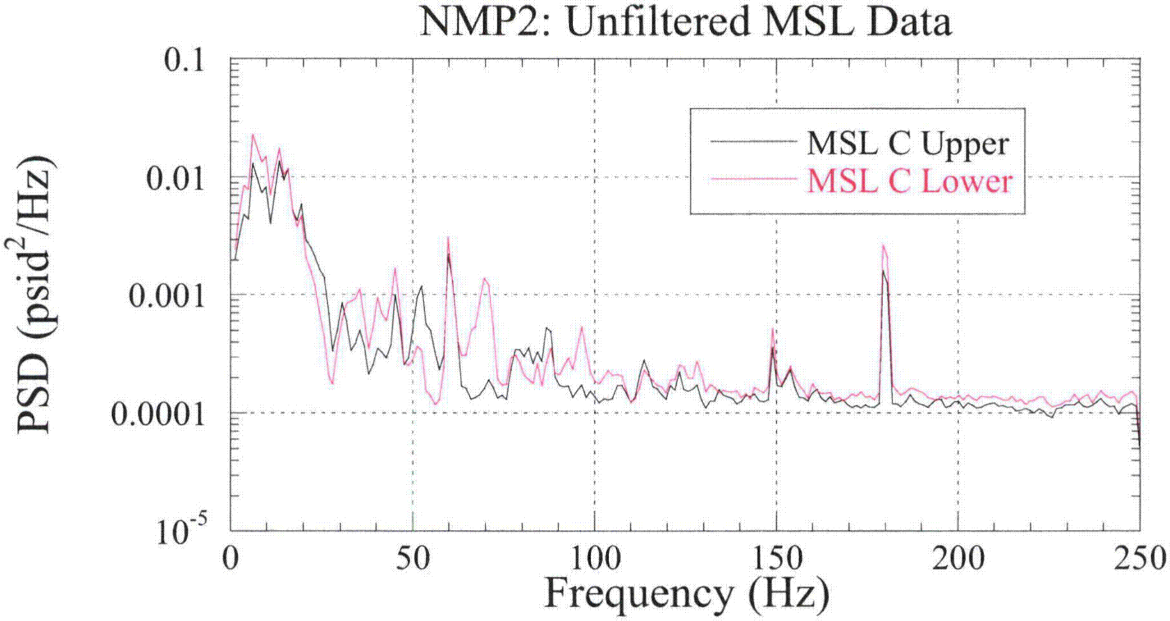


Figure 3.1a: Unfiltered data measured on the NMP2 main steam lines at CLTP conditions for main steam line A (top) and main steam line B (bottom).



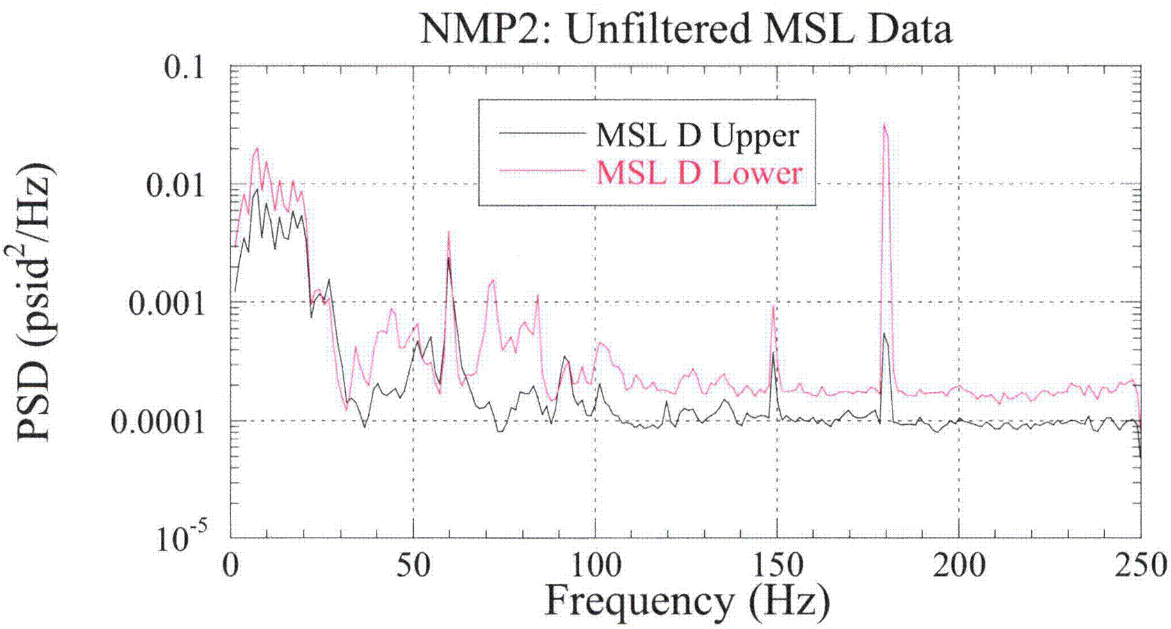


Figure 3.1b: Unfiltered data measured on the NMP2 main steam lines at CLTP conditions for main steam line C (top) and main steam line D (bottom).

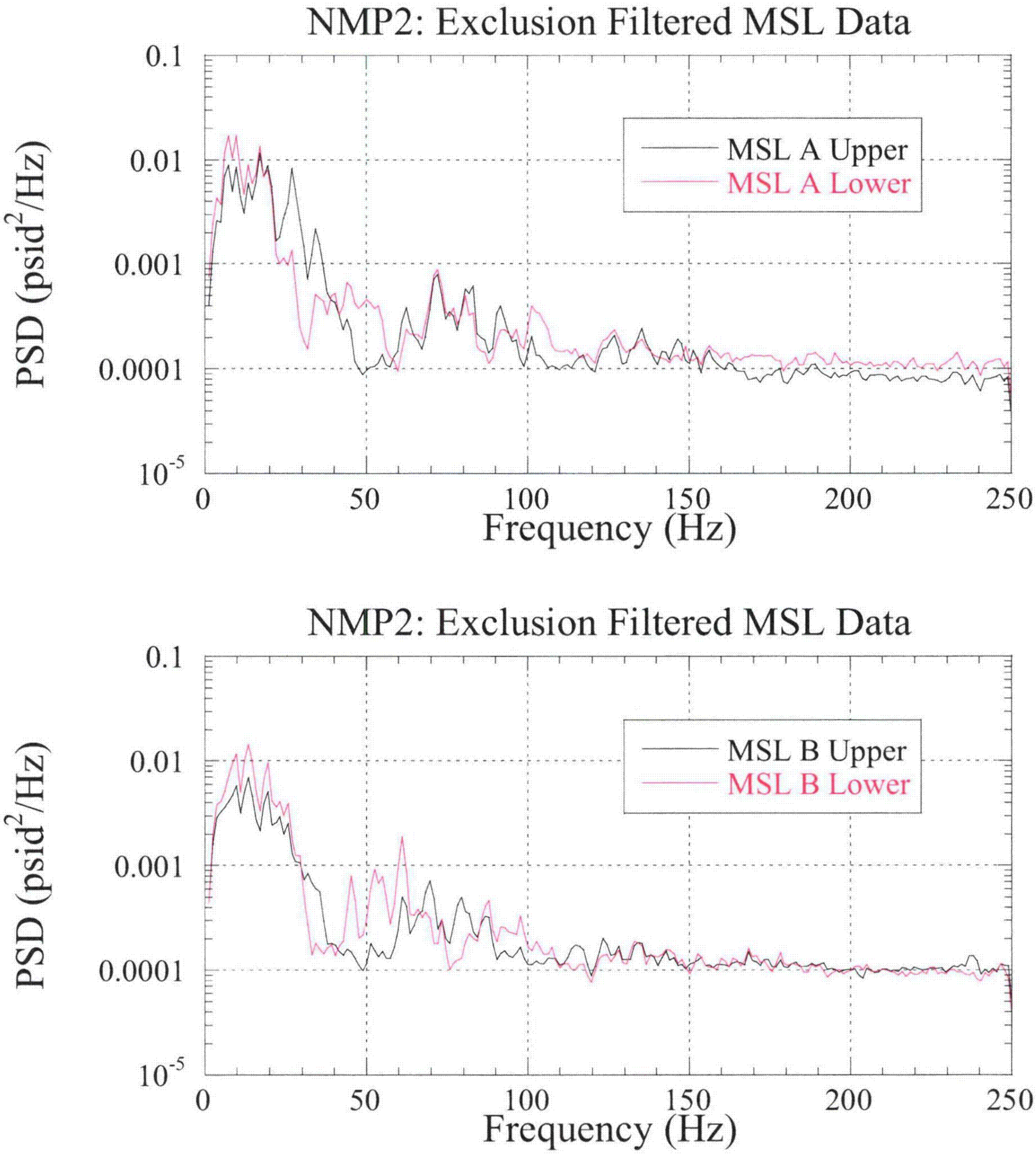


Figure 3.2a: Exclusion filtered data measured on the NMP2 main steam lines at CLTP conditions for main steam line A (top) and main steam line B (bottom).

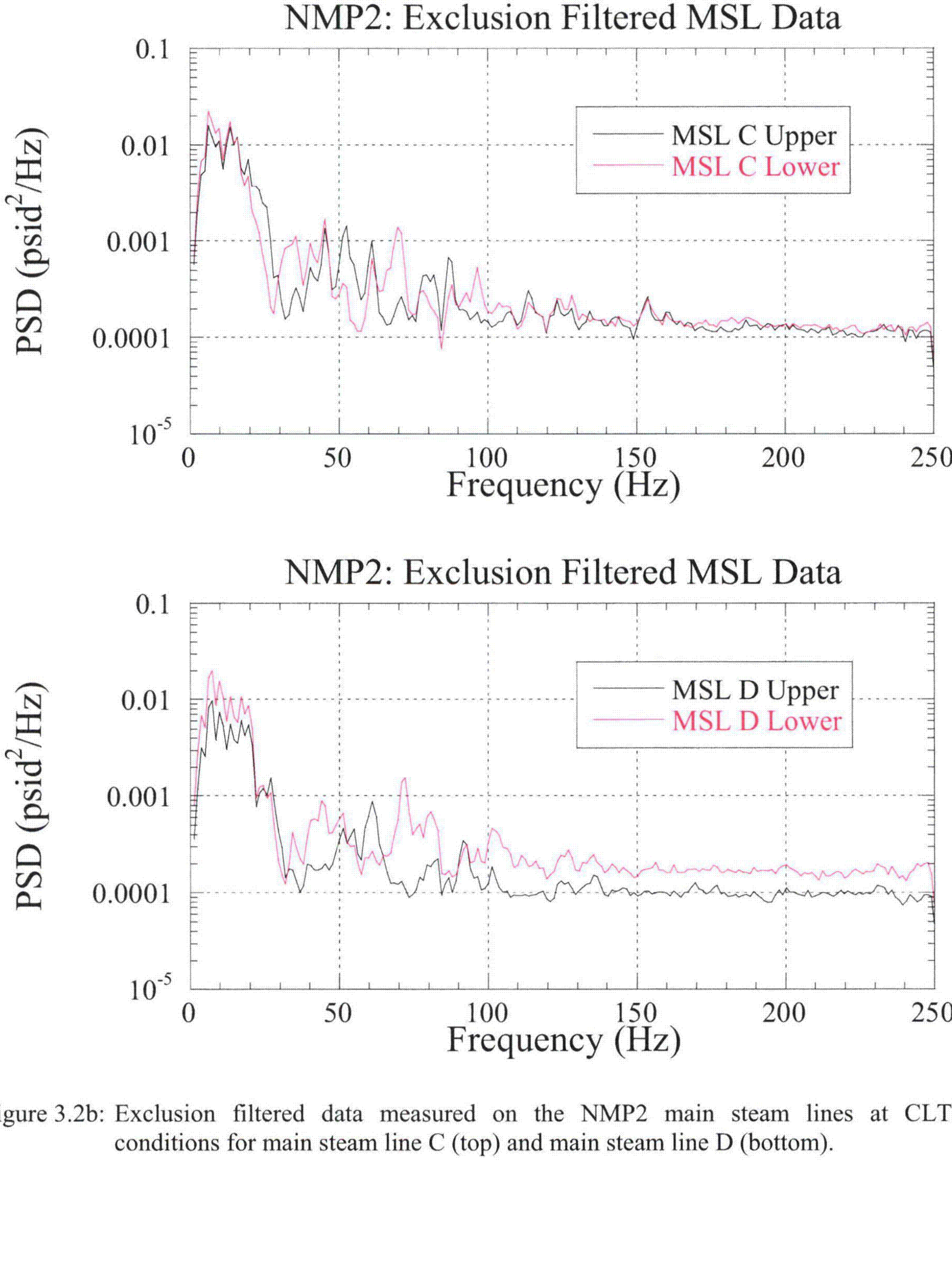
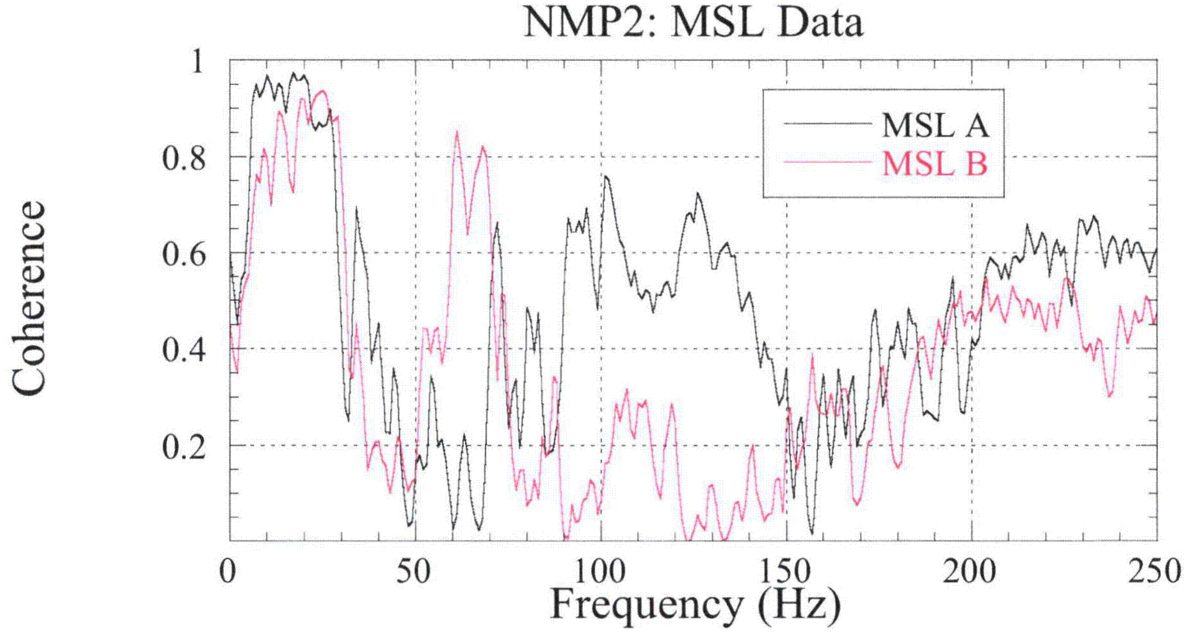


Figure 3.2b: Exclusion filtered data measured on the NMP2 main steam lines at CLTP conditions for main steam line C (top) and main steam line D (bottom).



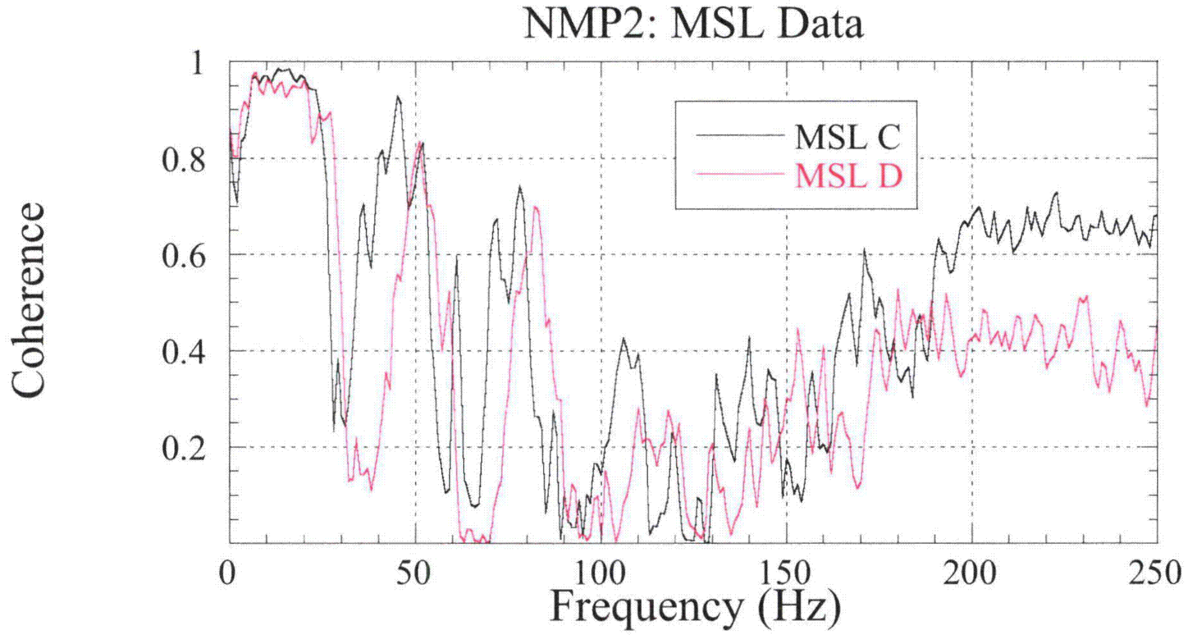


Figure 3.3: Coherence between the two strain gage signals on the NMP2 main steam lines at CLTP conditions for main steam lines A and B (top) and main steam lines C and D (bottom).

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Figure 3.4a: Coherence filtered data measured on the NMP2 main steam lines at CLTP conditions for main steam line A (top) and main steam line B (bottom).

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Figure 3.4b: Coherence filtered data measured on the NMP2 main steam lines at CLTP conditions for main steam line C (top) and main steam line D (bottom).

4. Results

The measured main steam line pressure data were used to drive the validated acoustic circuit methodology for the NMP2 steam dome coupled to the main steam lines to make a pressure load prediction on the NMP2 dryer. A low resolution load, developed at the nodal locations identified in Figures 4.1 to 4.4, produces the maximum differential pressure RMS pressure levels across the dryer as shown in Figure 4.5. PSDs of the peak loads on either side of the dryer are shown in Figure 4.6, while PSDs of the closure plate loads are shown in Figure 4.7.

Note that these loads include the bias and uncertainty corrections to be discussed in Section 5 of this report.

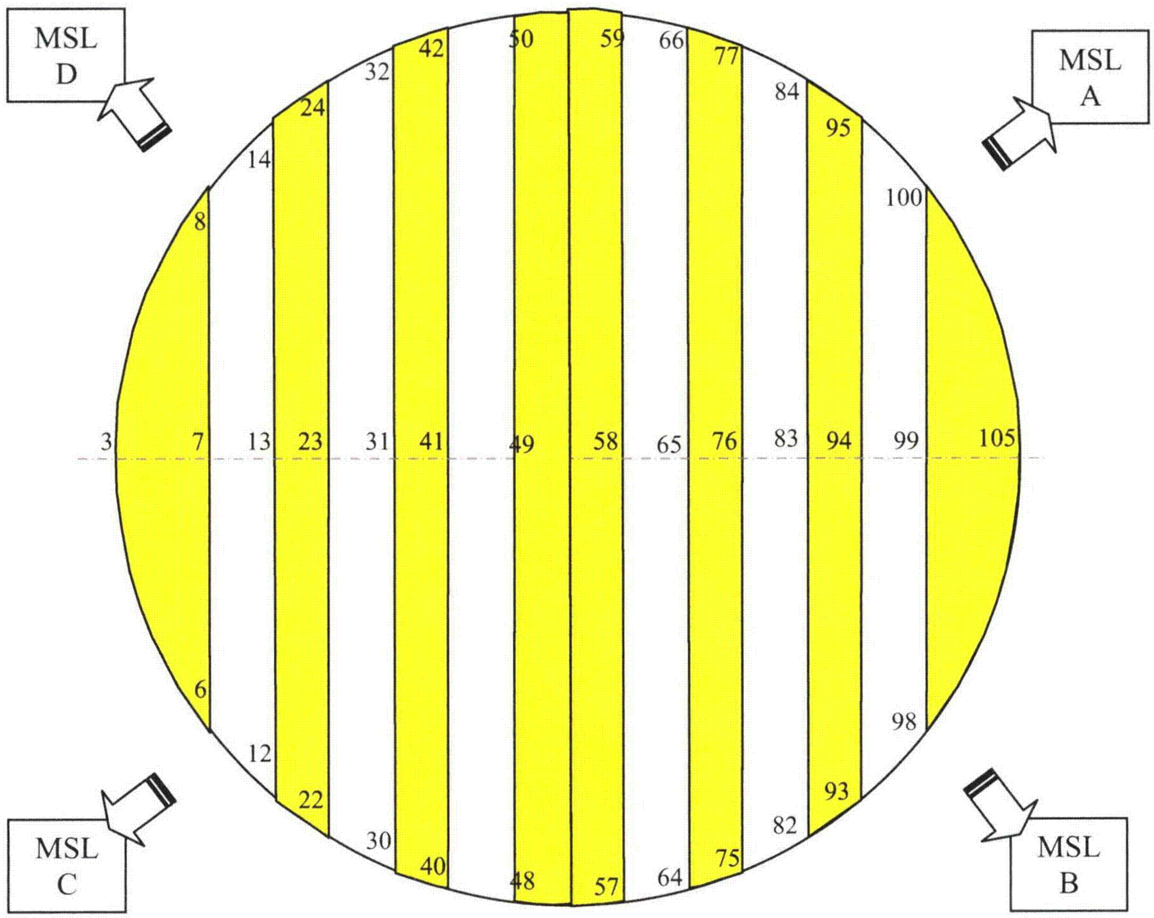

Figure 4.1. Cover and base plate low resolution load pressure node locations on the NMP2 dryer, with pressures acting downward in the notation defined here. Main steam line A is off the upper right corner of the figure; main steam line B off the lower right corner of the figure; main steam line C off the lower left corner of the figure; and main steam line D off the upper left corner of the figure. The cover plate on the A/B side of the dryer is identified by the nodes 98-99-100-105; the cover plate on the C/D side of the dryer is identified by the nodes 3-8-7-6. Base plates are identified by the nodes 64-65-66-77-76-75 and 82-83-84-95-94-93 (A/B side), 48-49-50-59-58-57 (center), and 12-13-14-24-23-22 and 30-31-32-42-41-40 (C/D side). The high resolution grid mesh (for subsequent finite element analysis) is spaced 3 inches on the cover plates, 6 inches on the first base plates, and 12 inches on the rest of the base plates.

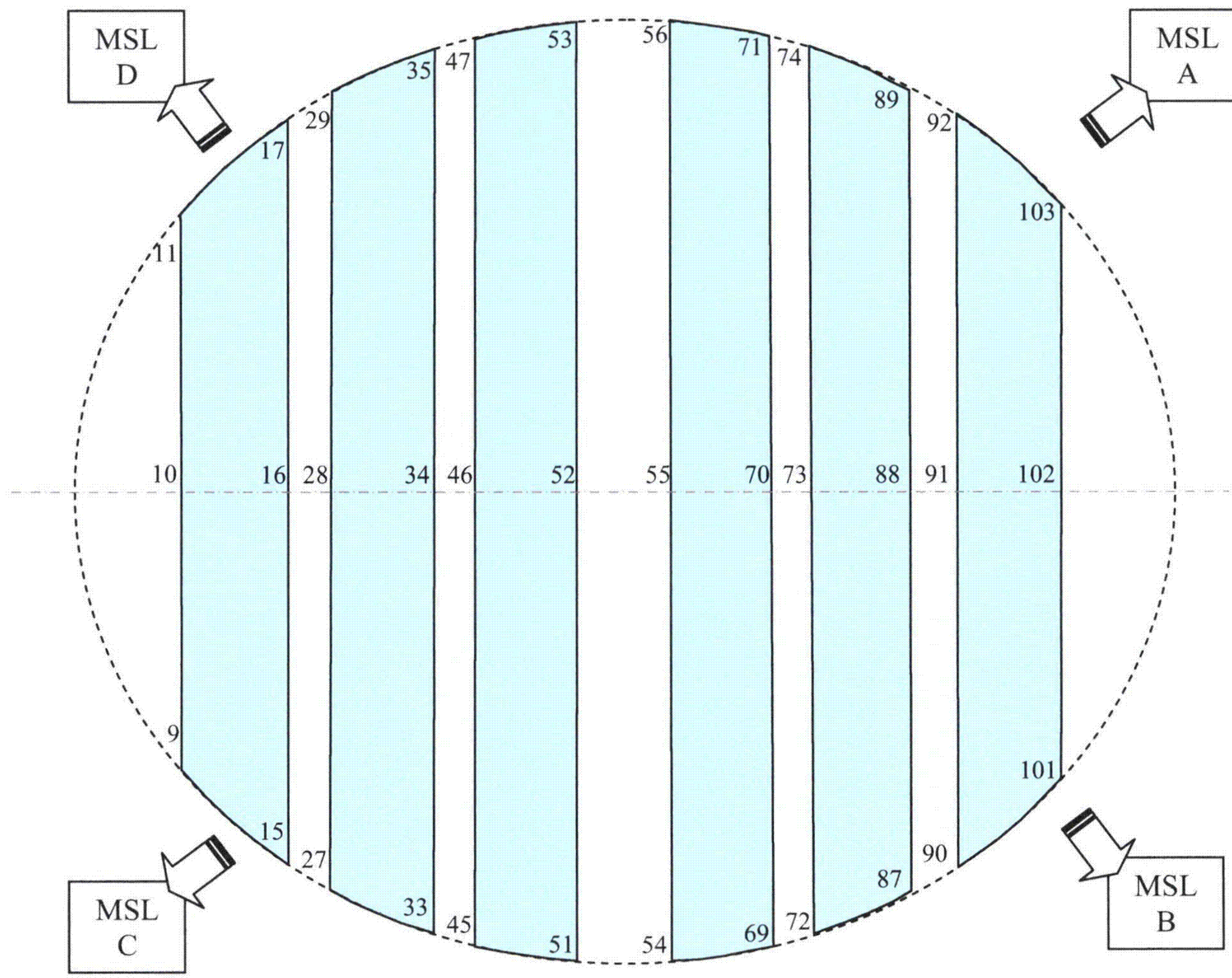

Figure 4.2. Top plate low resolution load pressure node locations on the NMP2 dryer, with pressures acting downward in the notation defined here. Main steam line A is off the upper right corner of the figure; main steam line B off the lower right corner of the figure; main steam line C off the lower left corner of the figure; and main steam line D off the upper left corner of the figure. Top plates on the A/B side of the dryer are identified by the nodes 90-91-92-103-102-101, 72-73-74-89-88-87, and 54-55-56-71-70-69. Top plates on the C/D side of the dryer are identified by the nodes 9-10-11-17-16-15, 27-28-29-35-34-33, and 45-46-47-53-52-51. The high resolution grid mesh (for subsequent finite element analysis) is spaced 3 inches on the outer top plates, 6 inches on the first inner top plates, and 12 inches on the rest of the inner top plates.

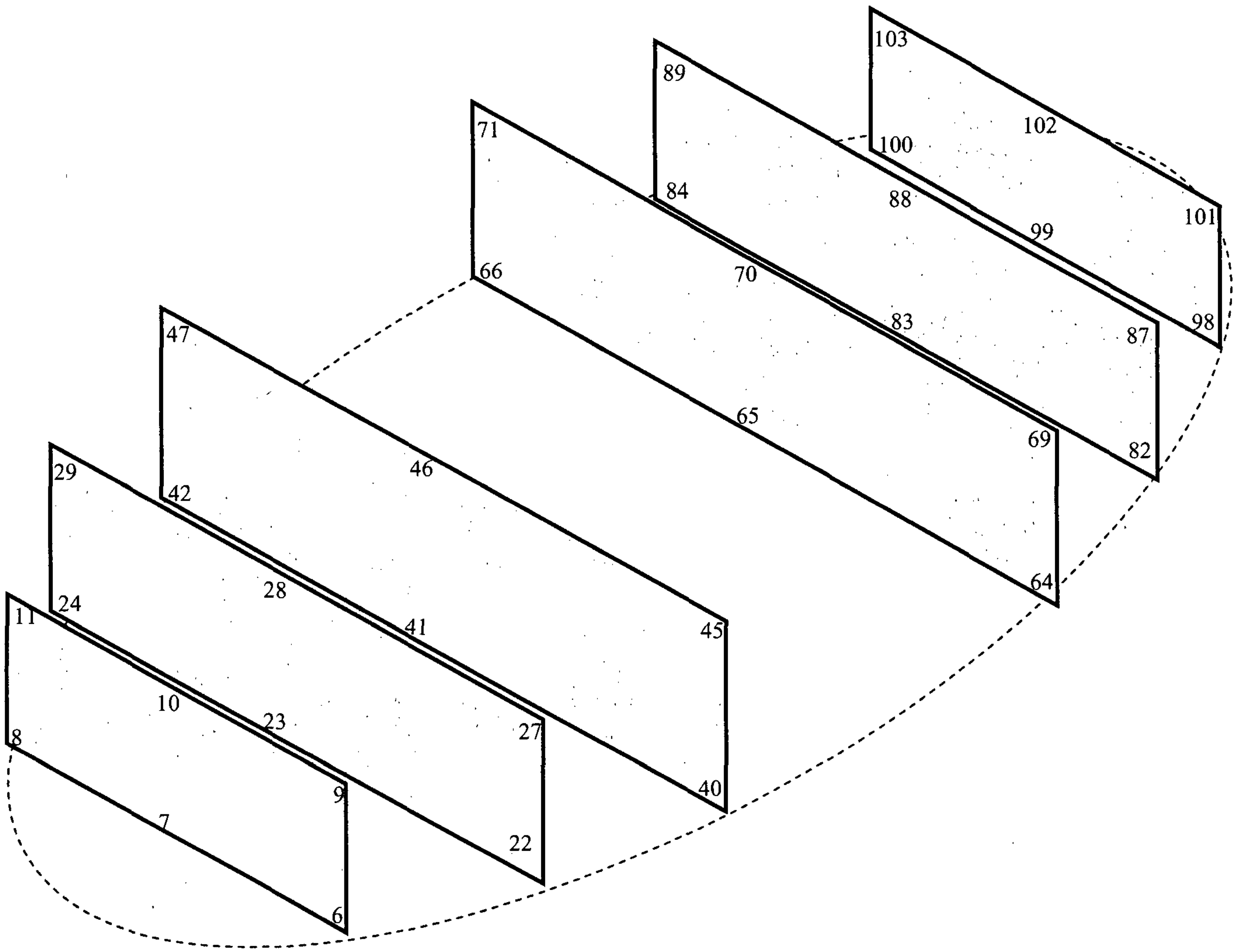

Figure 4.3. Outer and inner hood low resolution load pressure nodes on the NMP2 dryer. Main steam lines A and B are off the upper right corner of the figure; main steam lines C and D are off the lower left corner of the figure. Pressures act lower left to upper right on the outer hood identified by the nodes 6-7-8-11-10-9 (opposite C/D) and on the inner hoods identified by the nodes 22-23-24-29-28-27 and 40-41-42-47-46-45. Pressures act upper right to lower left on the outer hood identified by the nodes 98-99-100-103-102-101 (opposite A/B) and on the inner hoods identified by the nodes 82-83-84-89-88-87 and 64-65-66-71-70-69. The high resolution grid mesh (for subsequent finite element analysis) is spaced 3 inches on the outer hoods, 6 inches on the first inner hoods, and 12 inches on the inside hoods.

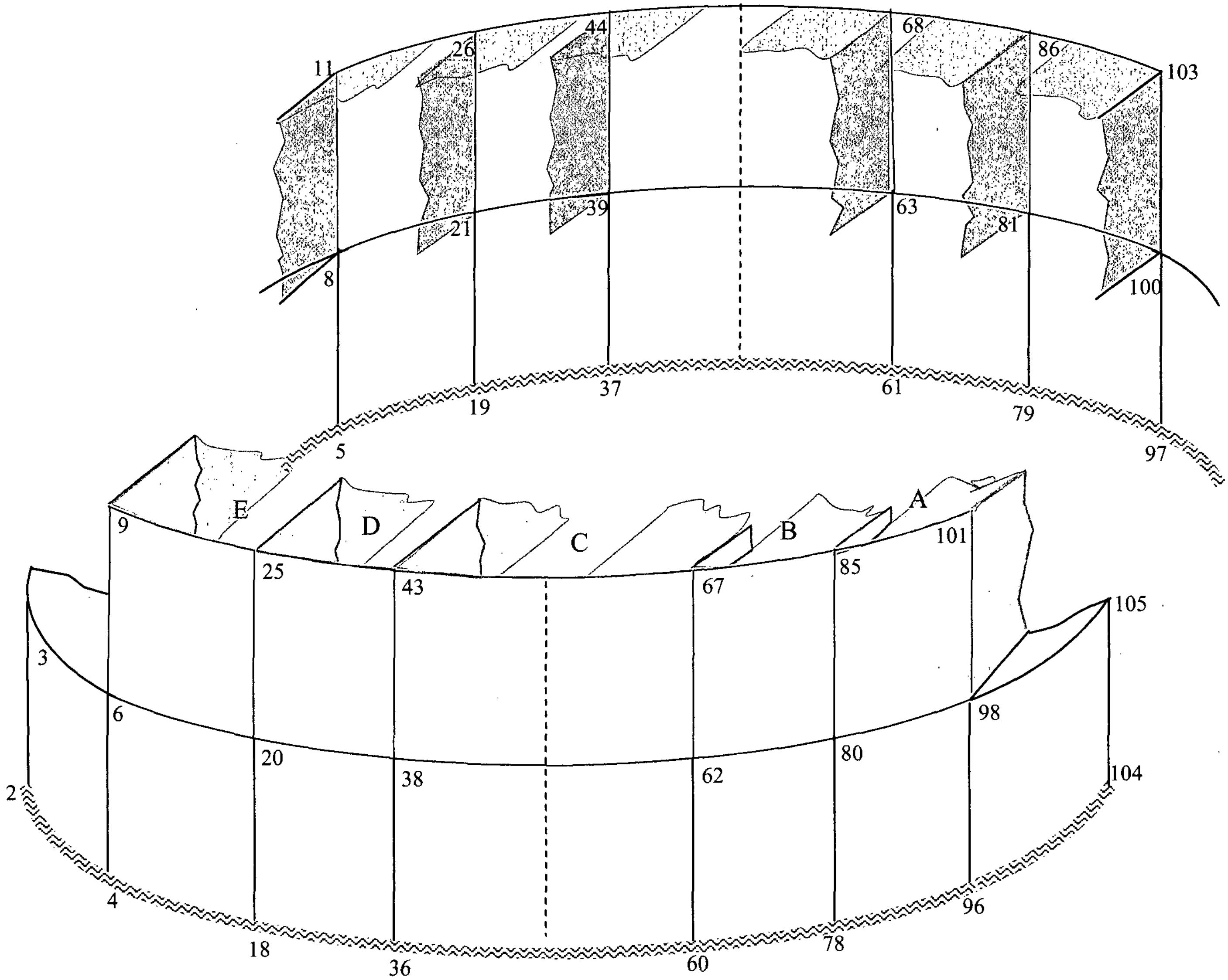

Figure 4.4. Skirt and end plate low resolution load pressure nodes on the NMP2 dryer, with pressures acting from the outside of the dryer to the inside. Main steam lines A and B are off the right side of the figure; main steam lines C and D are off the left side of the figure. Skirt nodes are 2-4-18-36-60-78-96-104 and 2-5-19-37-61-79-97-104. End plate nodes are 20-25 and 21-26, 38-43 and 39-44, 62-67 and 63-68, and 80-85 and 81-86. The high-resolution grid mesh (for subsequent finite element analysis) is spaced 3 inches on the outer portion of the skirt and end plates closest to the main steam lines, 6 inches on the sections nearer the center of the dryer, and 12 inches on the center of the dryer.

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Figure 4.5. Predicted loads on the low resolution grid identified in Figures 4.1 to 4.4, as developed by the ACM Rev. 4.1 model, to 250 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. Bias and uncertainty are included in these results.

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Figure 4.6. PSD of the maximum pressure loads predicted on the outer bank hood on the C-D side of the NMP2 dryer (top) and on the A-B side of the NMP2 dryer (bottom). Bias and uncertainty are included in these results.

5. Uncertainty Analysis

The analysis of potential uncertainty occurring at NMP2 consists of several contributions, including 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 ACM Rev. 4.1 model [3]. QC2 dryer data at Original Licensed Thermal Power (OLTP) conditions were used to generate an uncertainty analysis for NMP2.

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Bias is computed by taking the difference between the measured and predicted RMS pressure values for the sixteen pressures, and dividing the mean of this difference by the mean of the predicted RMS. RMS is computed by integrating the PSD across the frequency range of interest and taking the square root

$$\mathrm{BIAS} = \frac{\frac{1}{N}\sum(\mathrm{RMS}_{\mathrm{measured}} - \mathrm{RMS}_{\mathrm{predicted}})}{\frac{1}{N}\sum \mathrm{RMS}_{\mathrm{predicted}}}$$

where $\mathrm{RMS}_{\mathrm{measured}}$ is the RMS of the measured data and $\mathrm{RMS}_{\mathrm{predicted}}$ is the RMS of the predicted data. Summations are over the number of pressures examined.

Uncertainty is defined as the fraction computed by the standard deviation

$$\mathrm{UNCERTAINTY} = \frac{\sqrt{\frac{1}{N}\sum(\mathrm{RMS}_{\mathrm{measured}} - \mathrm{RMS}_{\mathrm{predicted}})^2}}{\frac{1}{N}\sum \mathrm{RMS}_{\mathrm{predicted}}}$$

ACM Rev. 4.1 bias and uncertainty results are compiled for specified frequency ranges of interest [7], and summarized in Table 5.1. Other random uncertainties, specific to NMP2, are summarized in Table 5.2 and are combined with the ACM results by SRSS methods to determine an overall uncertainty for NMP2, which is shown in Table 5.3.

Table 5.1. NMP2 bias and uncertainty for specified frequency intervals. A negative bias indicates that the ACM overpredicts the QC2 data in that interval.

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Table 5.2. Bias and uncertainty contributions to total uncertainty for NMP2 plant data.

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Table 5.3. NMP2 total uncertainty for specified frequency intervals.

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6. Conclusions

The C.D.I. acoustic circuit analysis, using full-scale measured data for NMP2:

a) [[

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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.

7. References

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13. NRC Request for Additional Information on the Hope Creek Generating Station, Extended Power Uprate. 2007. RAI No. 14.79.

14. NRC Request for Additional Information on the Hope Creek Generating Station, Extended Power Uprate. 2007. RAI No. 14.110.