Attachment 18

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REQUEST FOR LICENSE AMENDMENT
EXTENDED POWER UPRATE

Hydrodynamic Loads on Hope Creek Unit 1 Steam Dryer to 200 Hz
CDI Report 05-17, Revision 1
October 2005

C.D.I. Report No. 05-17

Hydrodynamic Loads on Hope Creek Unit 1 Steam Dryer to 200 Hz

Revision 1

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Executive Summary

Measured in-plant strain gage / pressure time-history data in the four main steam lines of Hope Creek Unit 1 (HC1) are processed by a dynamic model of the steam delivery system to predict loads on the 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 model is used to predict the fluctuating pressures anticipated across components of the steam dryer in the reactor vessel. The hydrodynamic load data may then be used by a structural analyst to assess the structural adequacy of the steam dryer in HC1.

This effort provides PSEG with a dryer dynamic load definition that comes directly from measured in-plant data and the application of a validated acoustic circuit model, at a power level where the strain gage / pressure data were acquired.

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I. 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 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 model under development by Continuum Dynamics, Inc. for several years [1]. The results of this benchmark exercise [2] confirmed the predictive ability of the acoustic circuit model for pressure loading across the dryer. This model, validated against the Exelon full scale data, is used in this effort.

This report applies this validated acoustic circuit model to the Hope Creek Unit 1 (HC1) steam dryer and main steam line geometry. Data obtained from the four main steam lines were used to generate predictions of the pressure loading on the HC1 dryer at seven power levels from 50% to 100%. The highest loading was predicted for the 96% power level. The magnitude of these load predictions is similar to previous load predictions for Dresden Unit 2 and Unit 3, although greater uncertainty exists in the HC1 loads as a consequence of the locations of the strain gages – more than 200 feet from the steam dome.

II. Modeling Considerations

The HC1 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.

2.1 Helmholtz Analysis

A cross-section of the steam dome (and steam dryer) is shown below in Figure 2.1, with HC1 dimensions as shown. The complex three-dimensional geometry is rendered onto a uniformly-spaced rectangular grid (with mesh spacing of approximately 1.5 inches), and a solution 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.

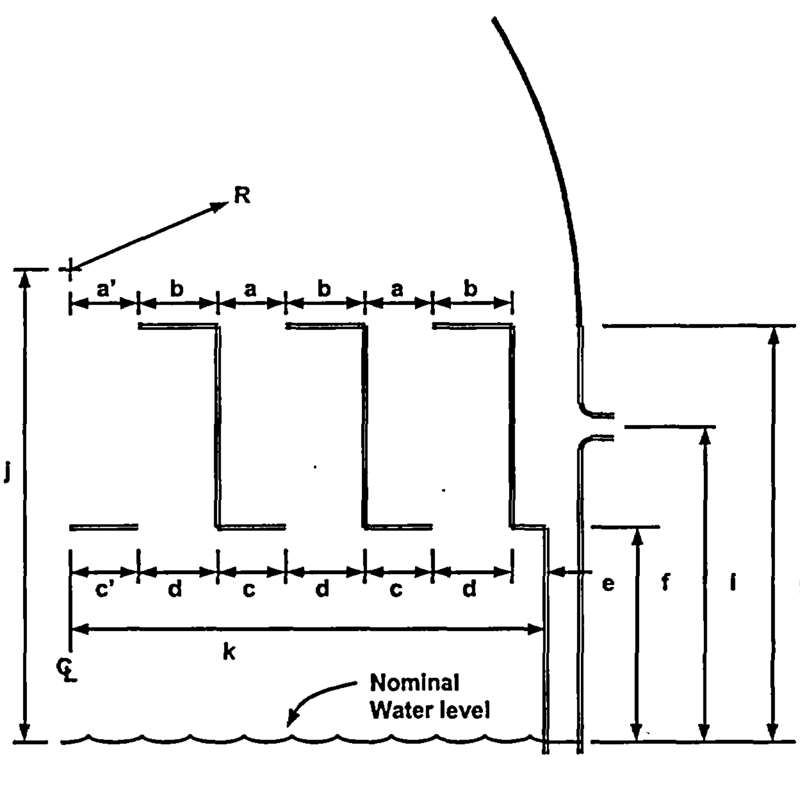


Figure 2.1. Cross-sectional description of the steam dome and dryer, with the verified HC1 dimensions of a' = 15.0, a = 17.5 in, b = 13.5 in, c' = 21.0 in, c = 15.0 in, d = 16.0 in, e = 21.0 in, f = 73.0 in, g = 163.0 in, i = 96.5 in, j = 183.0 in, k = 120.0 in, and R = 125.5 in.

This equation is solved for incremental frequencies from 0 to 200 Hz, 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 component dimensions, and in particular 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 $\bar{a}$.

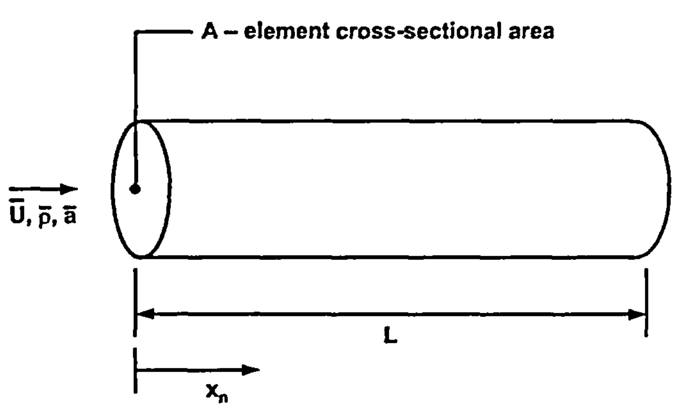


Figure 2.2. Schematic of an element in the acoustic circuit analysis, with length L and cross-sectional area A.

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 main steam line piping geometry is summarized in Table 2.1.

Table 2.1. Main steam line lengths at HC1. The main steam lines are 26 inch Schedule 80 (ID = 23.647 in) and 28 inch Schedule 80 (ID = 26.267 in).

Main Steam Line	Length of 26 inch Pipe (ft)	Length of 28 inch Pipe to First Strain Gage (ft)	Length of 28 inch Pipe to Second Strain Gage (ft)
A	168.05	39.33	89.33
B	180.09	39.33	89.33
C	175.88	39.33	89.33
D	164.21	39.33	89.33

III. Input Pressure Data

Strain gages were mounted on the four main steam lines. The seven data sets examined here is summarized in Table 3.1, and includes the eight strain gage measurements, as identified in Table 3.2. Recorded strain is converted to pressure by the formula

$$P = 2.537\,\varepsilon_h$$

where P is the pressure in psid and ε_h is the hoop strain in $\mu\varepsilon$ [3].

Table 3.1. Data sets considered for HC1.

Data Set	Feed Flow (10^6 lbs/hr)	Data Rate (samples/sec)	Pertinent Comments
20050707103347	14.40	1024	100% Power
20050211035248	14.12	1024	98% Power
20050210212726	13.83	1024	96% Power
20050207153500	12.96	1024	90% Power
20050906080538	10.90	1024	76% Power
20050201083053	9.42	1024	65% Power
20050131074623	7.42	1024	50% Power

Table 3.2. Strain gage identification for HC1.

Strain Gage Number	Strain Gage MSL Location	Strain Gage Channel Number
1	A: first strain gage	STGA-A01-233
2	A: second strain gage	STGA-A03-237
3	B: first strain gage	STGA-B01-62
4	B: second strain gage	STGA-B03-67
5	C: first strain gage	STGA-C01-582
6	C: second strain gage	STGA-C02-587
7	D: first strain gage	STGA-D01-402
8	D: second strain gage	STGA-D02-407

Examination of the frequency content of these data sets shows pressure spikes at 72, 108, and 142 Hz, depending on power level and strain gage. Past experience suggests that the ERV standpipes are typically the source of pressure spikes above 50 Hz. Because the strain gages are positioned downstream of the standpipes, the acoustic circuit model was modified to substitute a standpipe source for an inlet source, on each main steam line, above a frequency of 50 Hz. In addition, the large distances from the main steam line inlet to the locations of the strain gages – over 200 feet – also necessitated the zeroing of the acoustic damping in the main steam lines.

Table 3.3 summarizes the characteristics of the collected data at each of the seven power levels. Note that measured signals below 0.0009 psid^2/Hz are considered noise and have been filtered from the analysis. Table 3.3 suggests that examination of the pressures obtained from the strain gages is alone not sufficient to determine which power level leads to the maximum pressure load prediction. Rather, the acoustic circuit model must be used, and when it is, the 96% power level gives the highest pressure loading on the HC1 steam dryer (see Section 6 for additional details). This result is supported by [4]. The power spectral density functions (PSD) for 96% power are shown in Figure 3.1.

Table 3.3. Summary of the pressure data obtained from the eight strain gages at all power levels examined for HC1.

Maximum Pressure (psid)

Strain Gage Number	50% Power	65% Power	76% Power	90% Power	96% Power	98% Power	100% Power
1	0.394	0.271	0.313	0.473	0.553	0.486	0.355
2	0.307	0.388	0.0	0.965	1.784	1.016	1.082
3	0.458	1.087	0.0	2.268	1.690	1.348	1.392
4	0.396	0.831	2.608	1.518	0.701	0.611	0.732
5	0.310	0.724	0.117	0.309	0.514	0.192	0.155
6	0.493	0.638	0.380	0.852	1.073	0.832	0.713
7	0.398	0.321	0.185	0.432	0.519	0.459	0.361
8	0.514	0.527	0.0	0.357	0.303	0.369	0.227

RMS Pressure (psid)

Strain Gage Number	50% Power	65% Power	76% Power	90% Power	96% Power	98% Power	100% Power
1	0.108	0.129	0.073	0.099	0.140	0.120	0.098
2	0.094	0.113	0.0	0.265	0.315	0.267	0.282
3	0.115	0.281	0.0	0.362	0.412	0.320	0.326
4	0.139	0.210	0.448	0.223	0.194	0.158	0.166
5	0.094	0.204	0.042	0.078	0.160	0.059	0.047
6	0.145	0.157	0.099	0.189	0.300	0.217	0.171
7	0.112	0.105	0.075	0.117	0.146	0.119	0.101
8	0.129	0.145	0.0	0.085	0.081	0.096	0.061

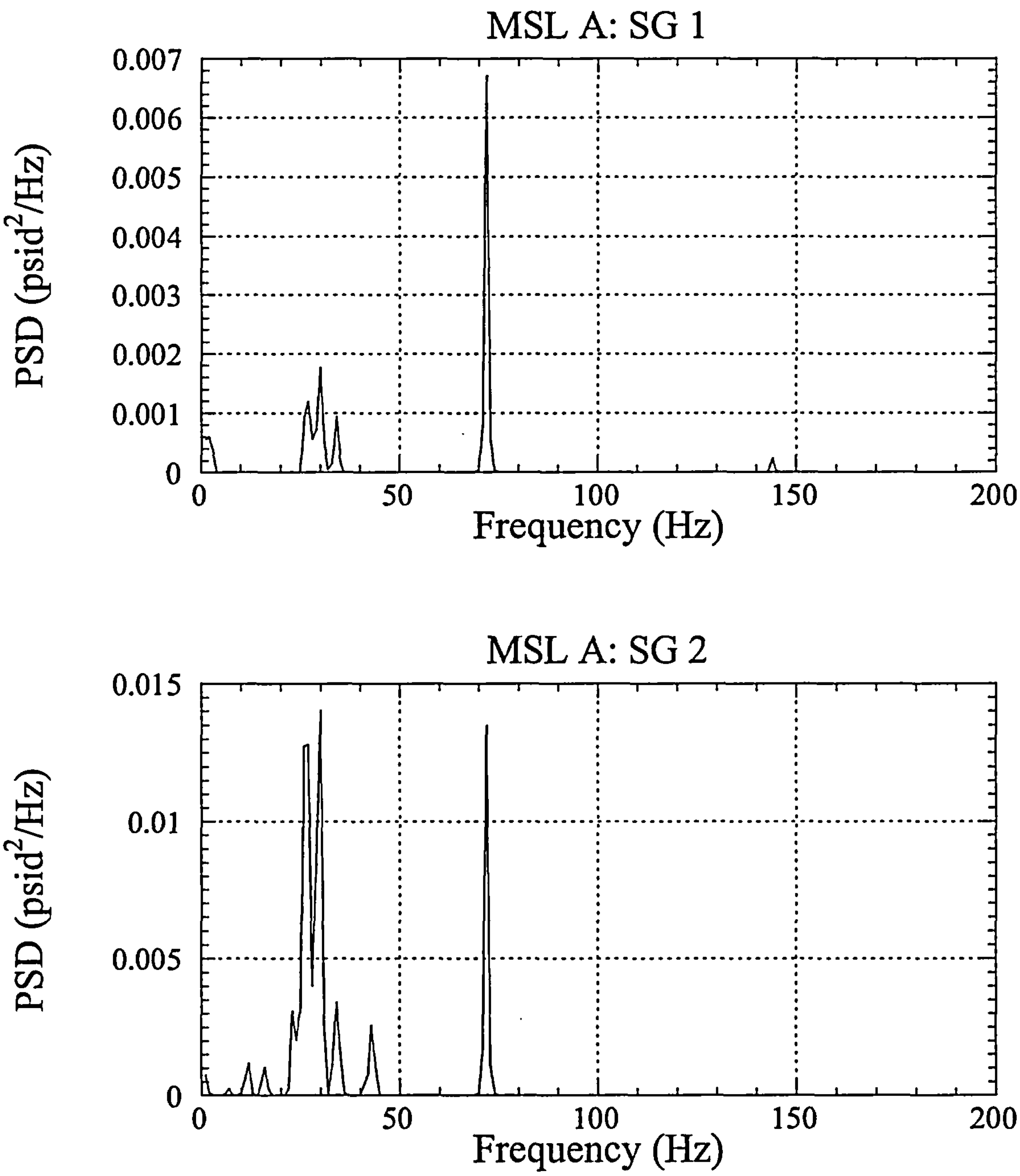
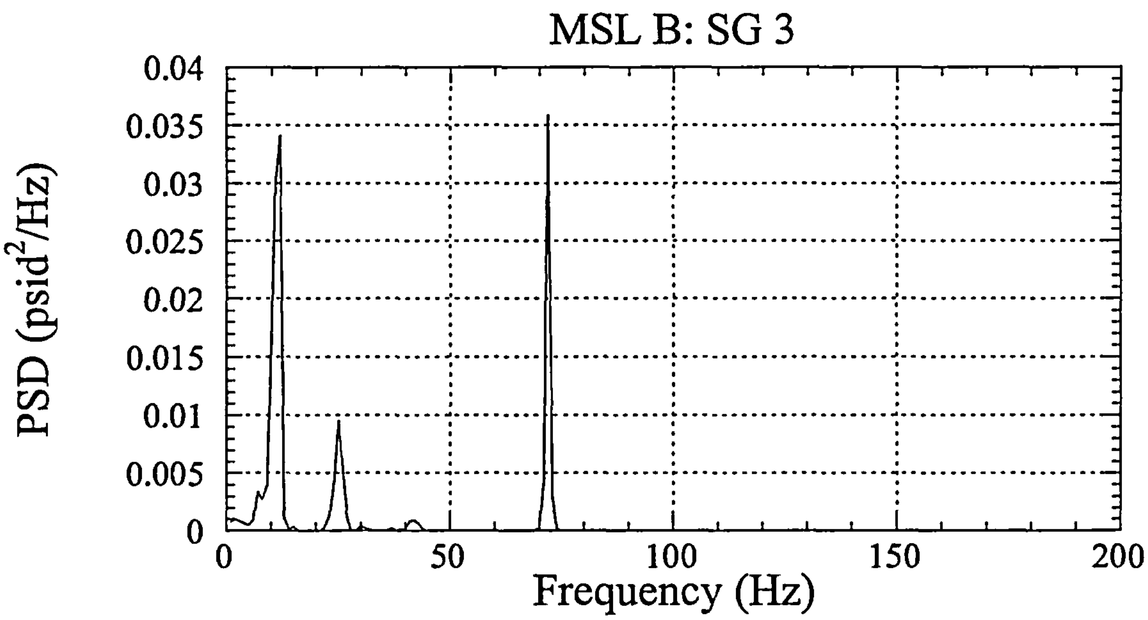


Figure 3.1a. PSD comparison of strain gage data at 96% power, converted to pressure, for main steam line A: strain gage number 1 (top) and strain gage number 2 (bottom).



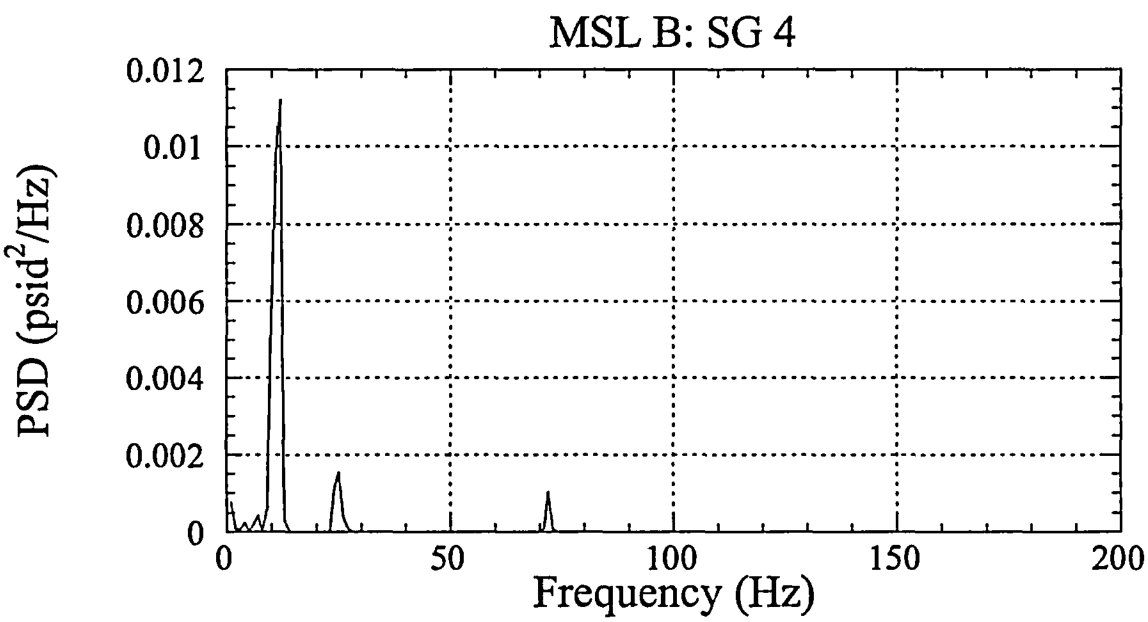


Figure 3.1b. PSD comparison of strain gage data at 96% power, converted to pressure, for main steam line B: strain gage number 3 (top) and strain gage number 4 (bottom).

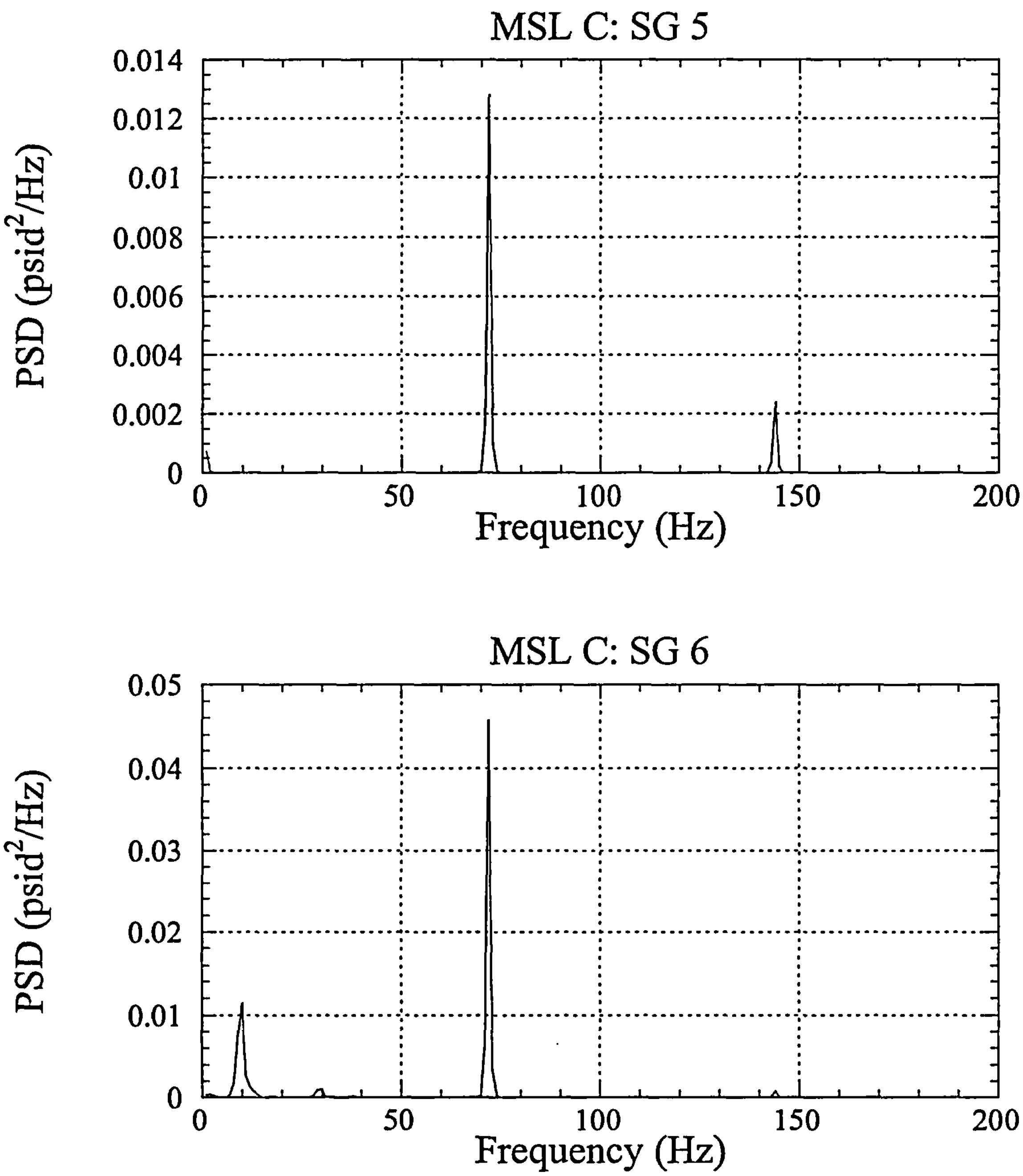
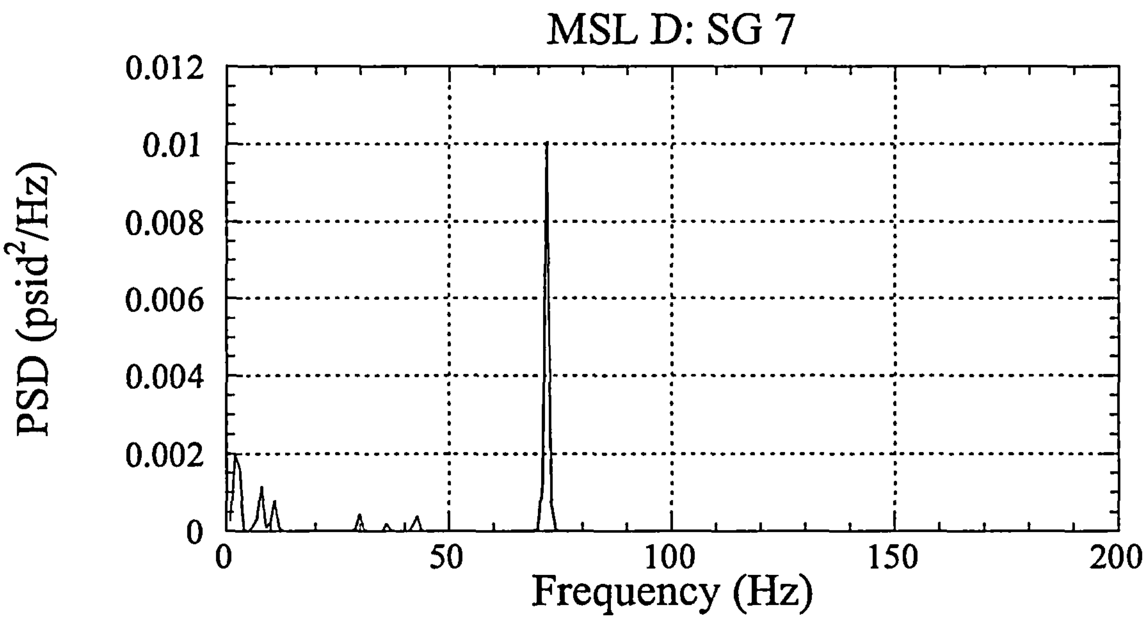


Figure 3.1c. PSD comparison of strain gage data at 96% power, converted to pressure, for main steam line C: strain gage number 5 (top) and strain gage number 6 (bottom).



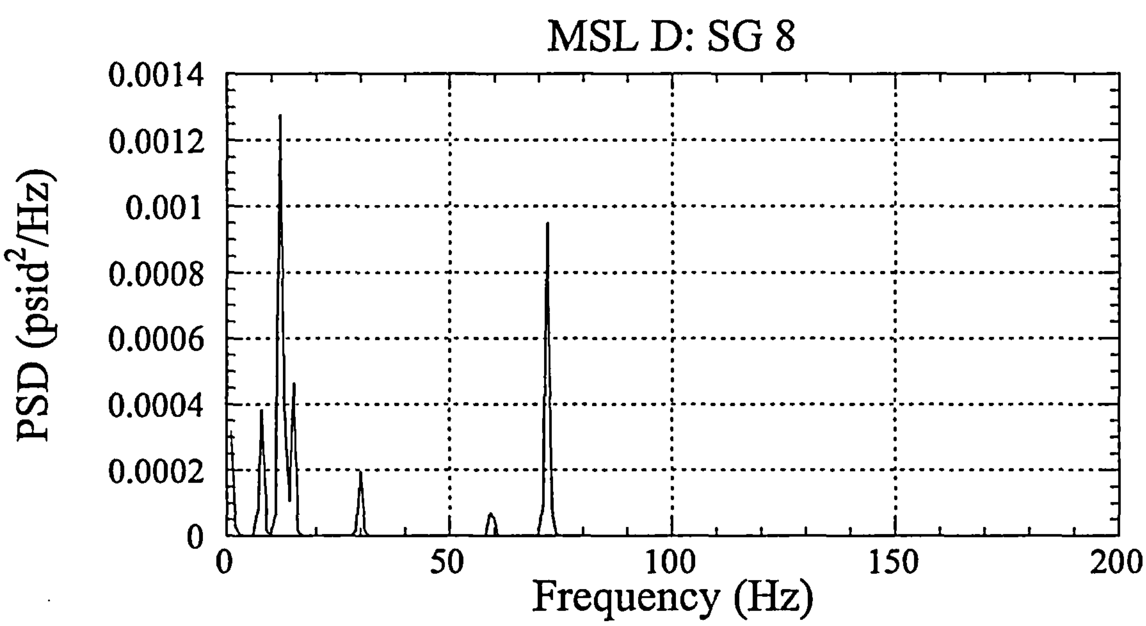


Figure 3.1d. PSD comparison of strain gage data at 96% power, converted to pressure, for main steam line D: strain gage number 7 (top) and strain gage number 8 (bottom).

IV. Results

The main steam line pressure data are used to drive the validated acoustic circuit model for the HC1 steam dome and main steam lines. The results are presented here on a low-resolution grid (shown schematically in Figures 4.1 to 4.4) by summarizing the peak and RMS pressures expected over the time interval provided in the original data. These nodal results for 96% power level are shown in Figure 4.5. The Minimum Error solution, as defined in [2], is used.

It may be seen that the peak loads are no higher than 1.2 psid. This loading level is consistent with previous results seen for Dresden Unit 2 (peak loads of 0.42 psid at OLTP and 0.74 psid at EPU) and Unit 3 (peak loads of 1.02 psid at OLTP and 1.12 psid at EPU), and is much less than predicted for Quad Cities Unit 1 and Unit 2 [5]. The peak loads on either side of the steam dryer in HC1 are shown in Figures 4.6 and 4.7.

Comparisons may be further shown at the front edge of the cover plates, opposite the A-B and C-D sides of the dryer, at nodes 8 and 99 (see Figures 4.1 and 4.5 for specific locations). On the A-B side of the dryer (node 99), the maximum predicted pressure difference across the cover plate is 1.142 psid at predominantly 72 Hz. On the C-D side of the dryer (node 8), the maximum predicted pressure difference across the cover plate is 0.610 psid, occurring at 29 Hz and 72 Hz.

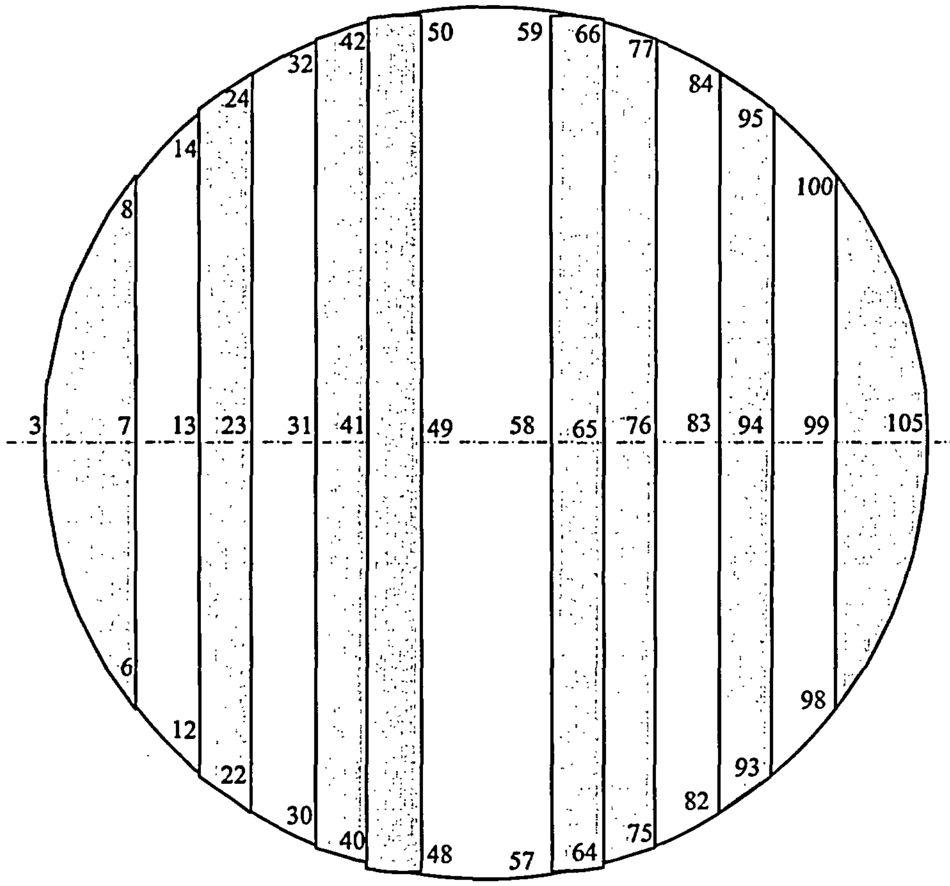


Figure 4.1. Bottom plates pressure node locations, with pressures acting downward in the notation defined here.

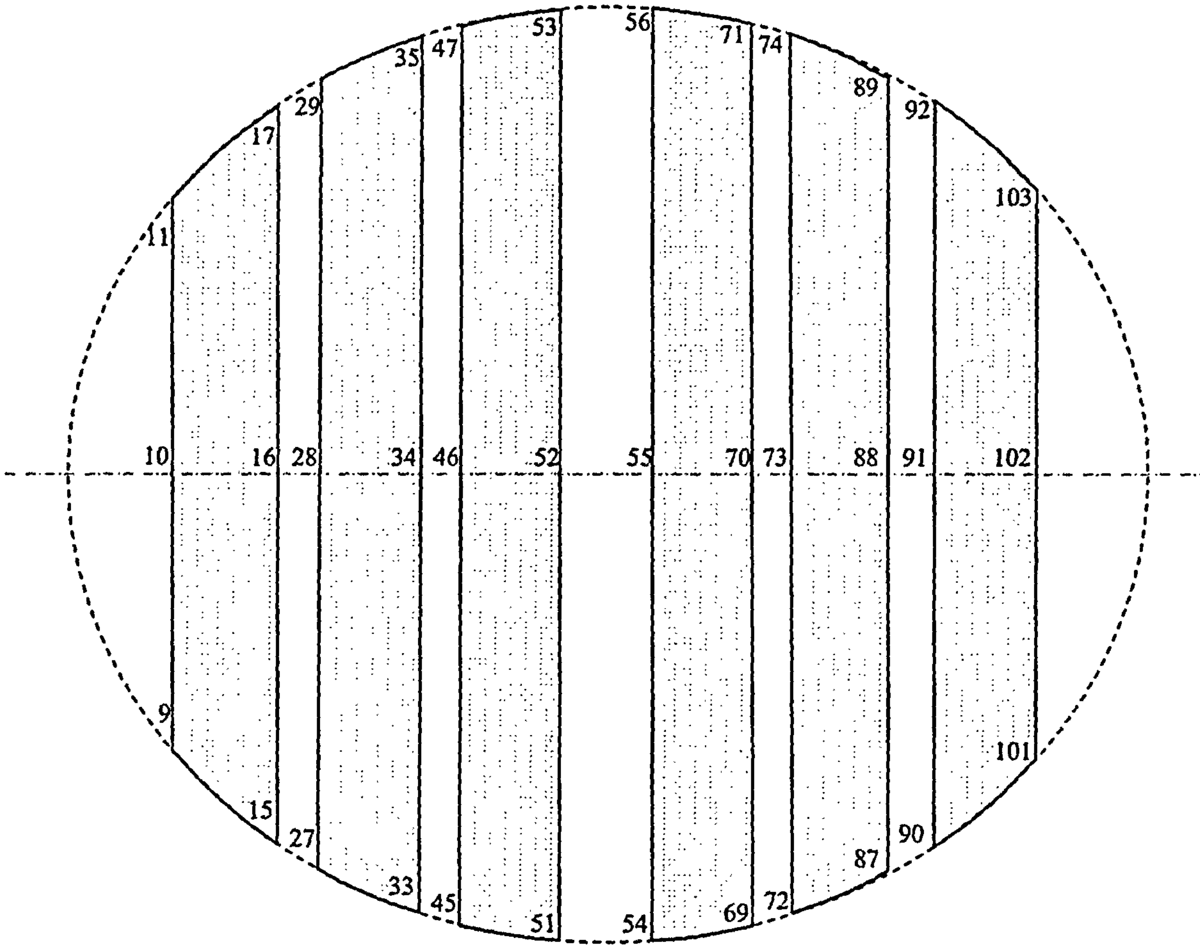


Figure 4.2. Upper plates pressure node locations, with pressures acting downward in the notation defined here.

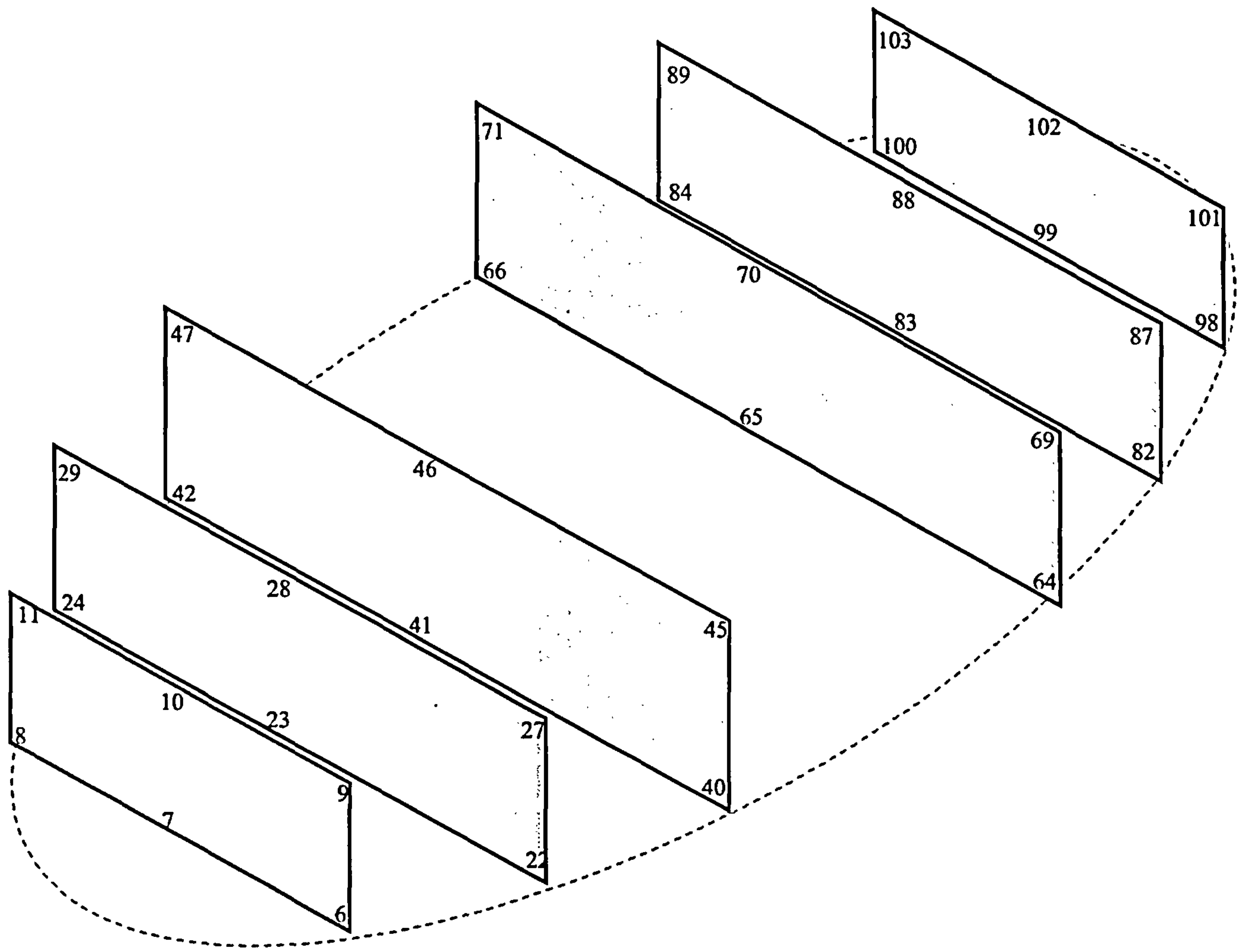


Figure 4.3. Vertical plates: Pressures acting left to right on panels 6-11, 22-29, and 40-47; acting right to left on panels 64-71, 82-89, and 98-103.

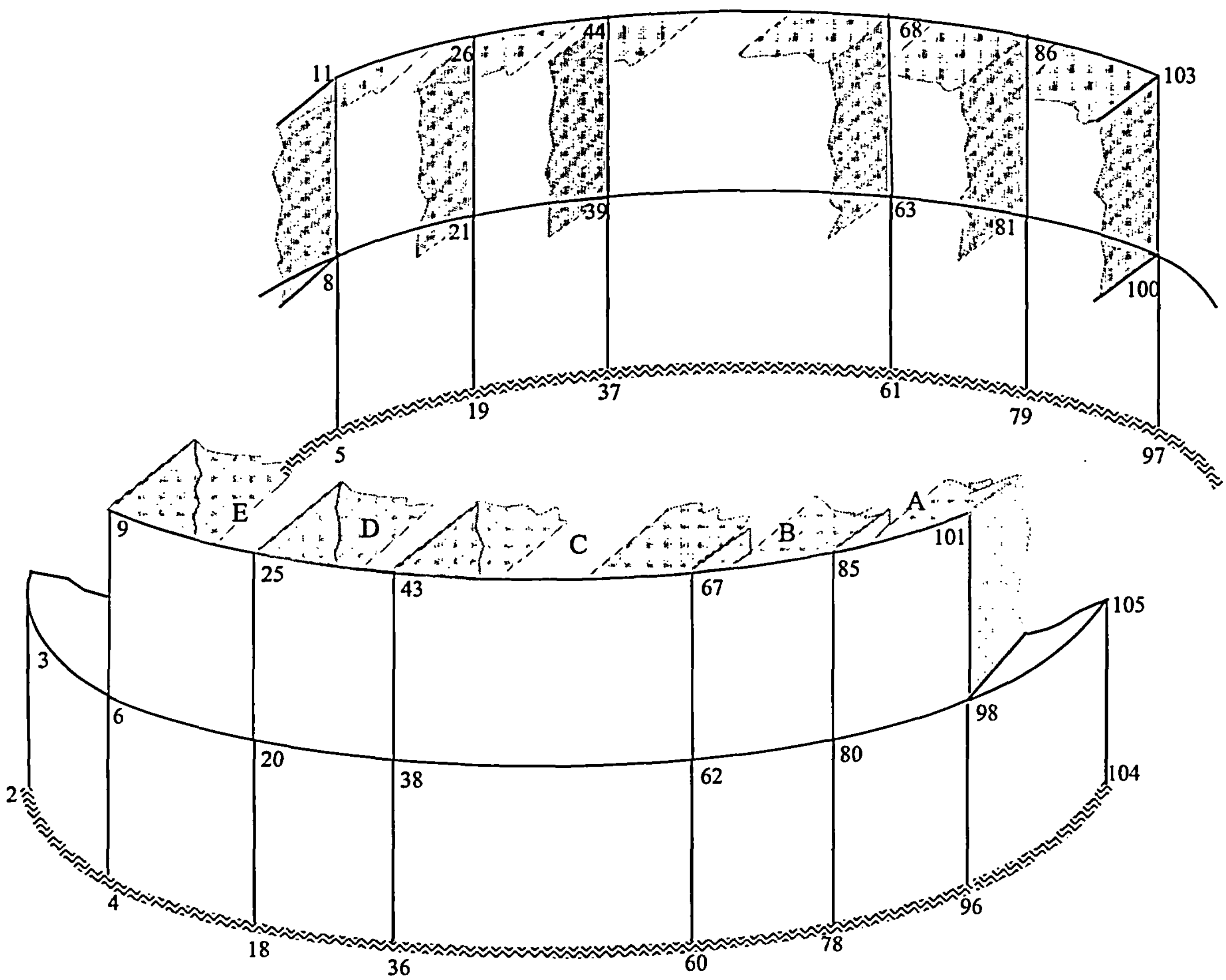


Figure 4.4. Skirt plates: Pressure acting on the outer dryer 0/180 surfaces and the skirt.

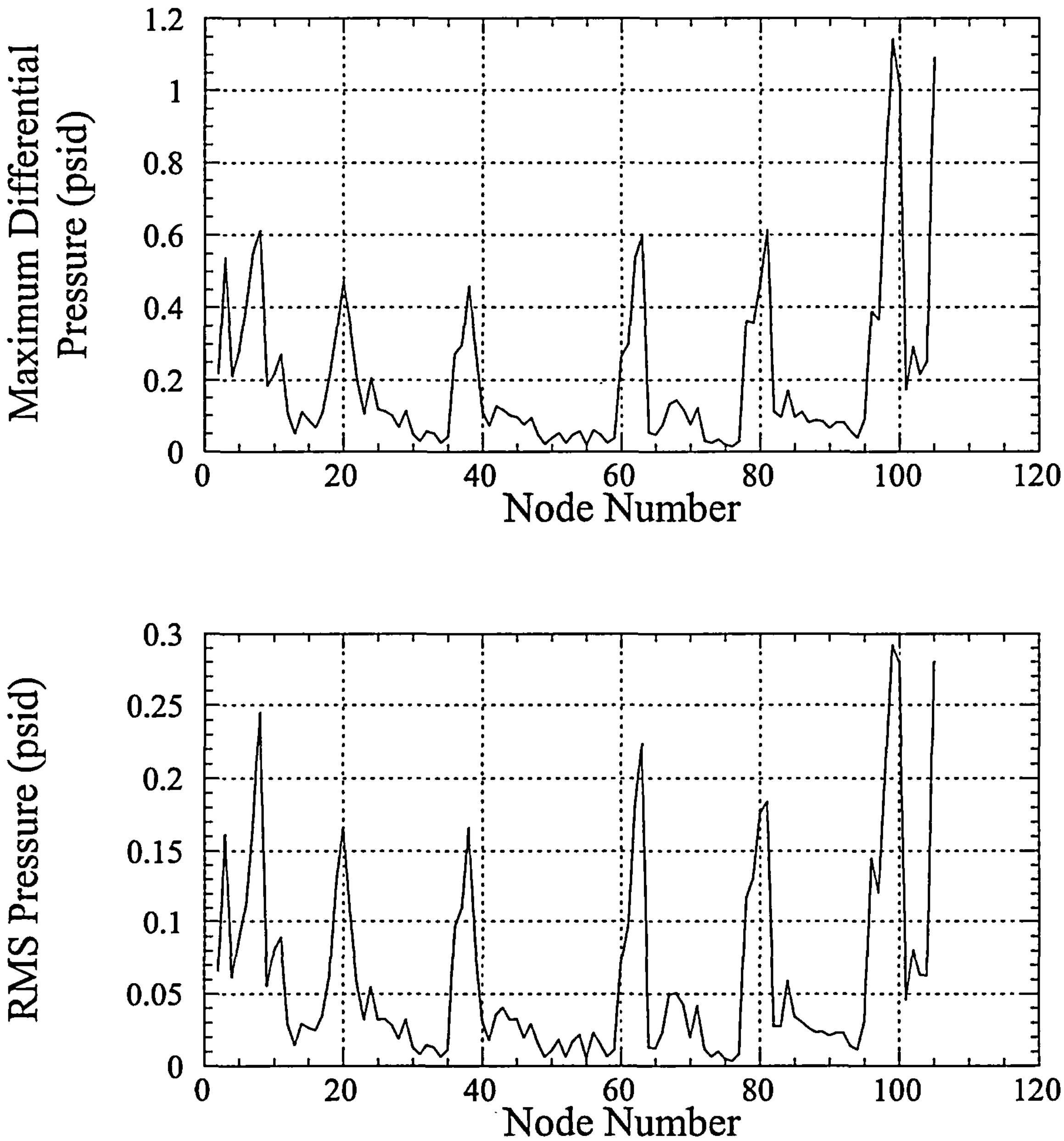


Figure 4.5. Predicted loads at 96% power as developed by the current methodology to 200 Hz. Node 8 is located at the back edge of the cover plate opposite the D main steam line, while node 99 is located at the back edge of the cover plate between the A and B main steam lines.

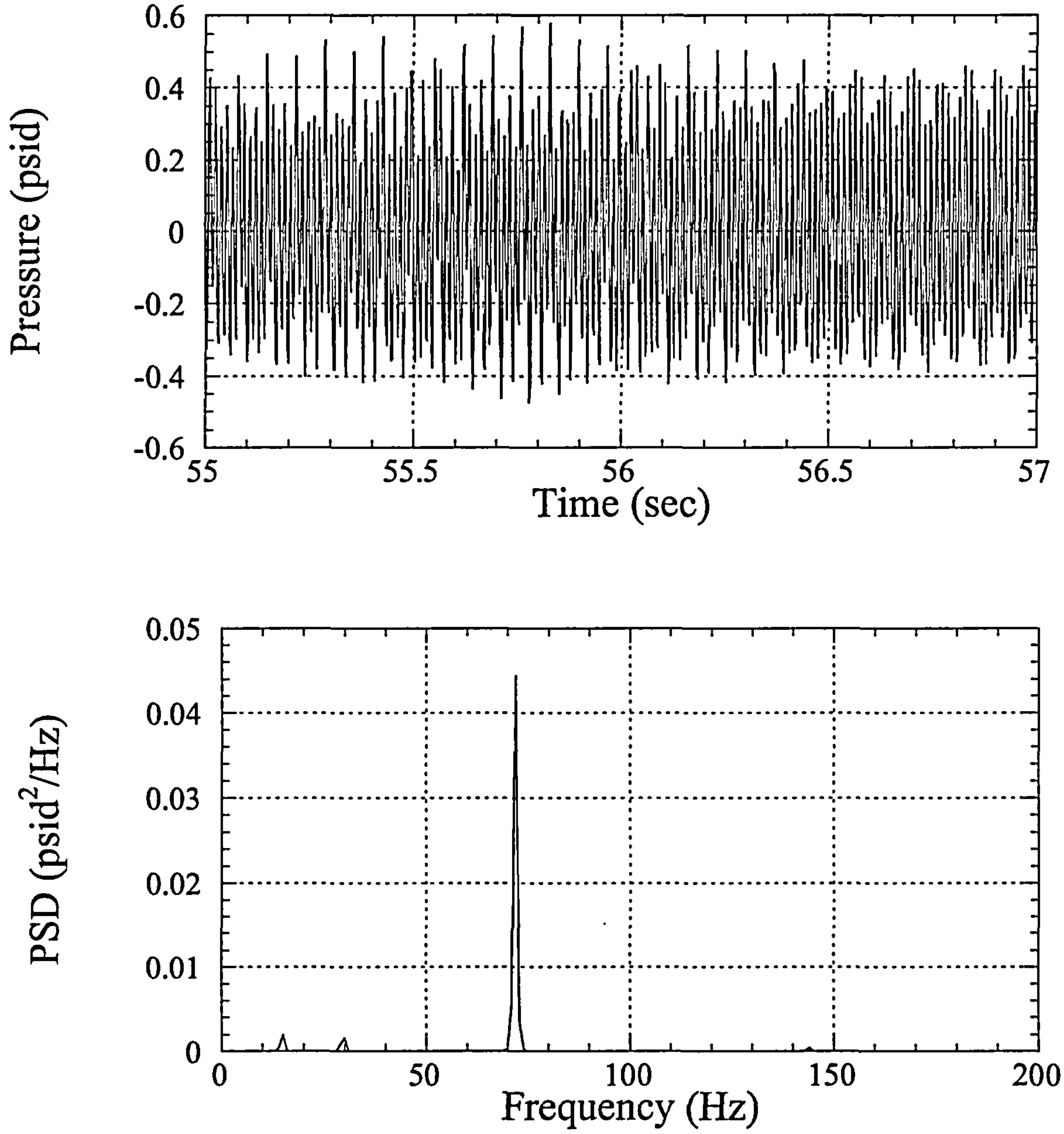


Figure 4.6. Time and PSD of the predicted pressure load at node 8.

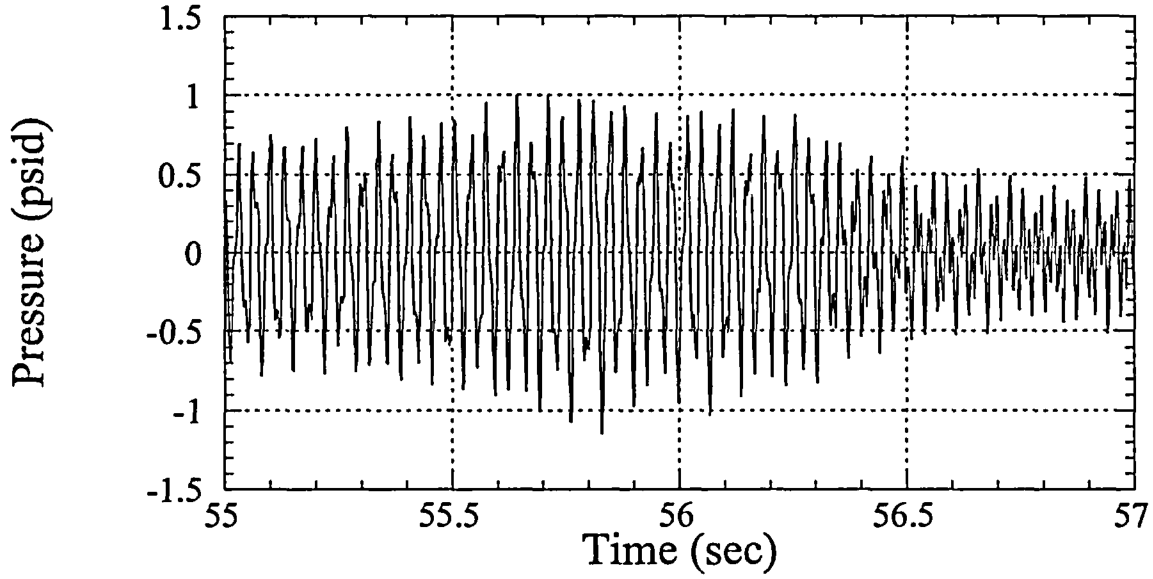


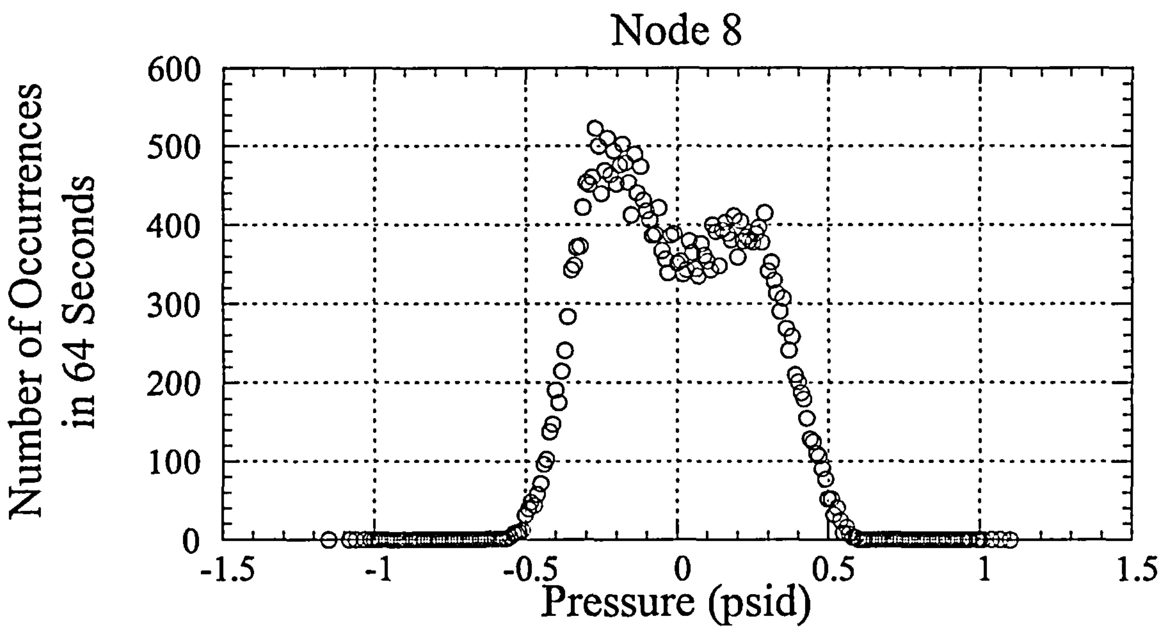
Figure 4.7. Time and PSD of the predicted pressure load at node 99.

V. Peak Loads Sensitivity and Exceedance

The 96% power results can be examined to develop the load exceedance probability function for peak pressure loads on either side of the steam dryer (nodes 8 and 99). For the predictions shown previously in Figures 4.6 and 4.7, respectively, the predicted discrete pressures (positive and negative) are sorted into bins of width 0.01 psid and plotted, as shown in Figure 5.1. The distributions for nodes 8 and 99 are normally distributed, and Gaussian functions of the form

$$p(P) = \frac{A}{\sigma\sqrt{2\pi}} e^{-P^2/2\sigma^2}$$

can be curvefit to the collected data, resulting in standard deviations of $\sigma = 0.2973$ psid for node 8 and $\sigma = 0.2946$ psid for node 99. Then, the time for a peak load P to occur can be found from the exponential portion of the above equation. The results are shown in Figure 5.2.



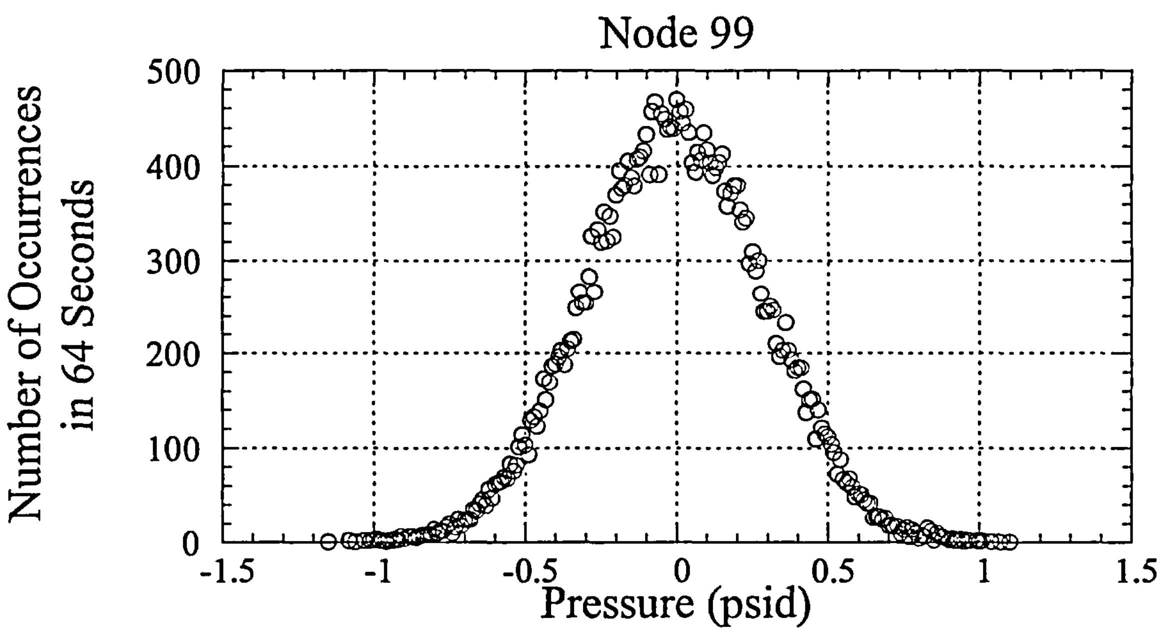
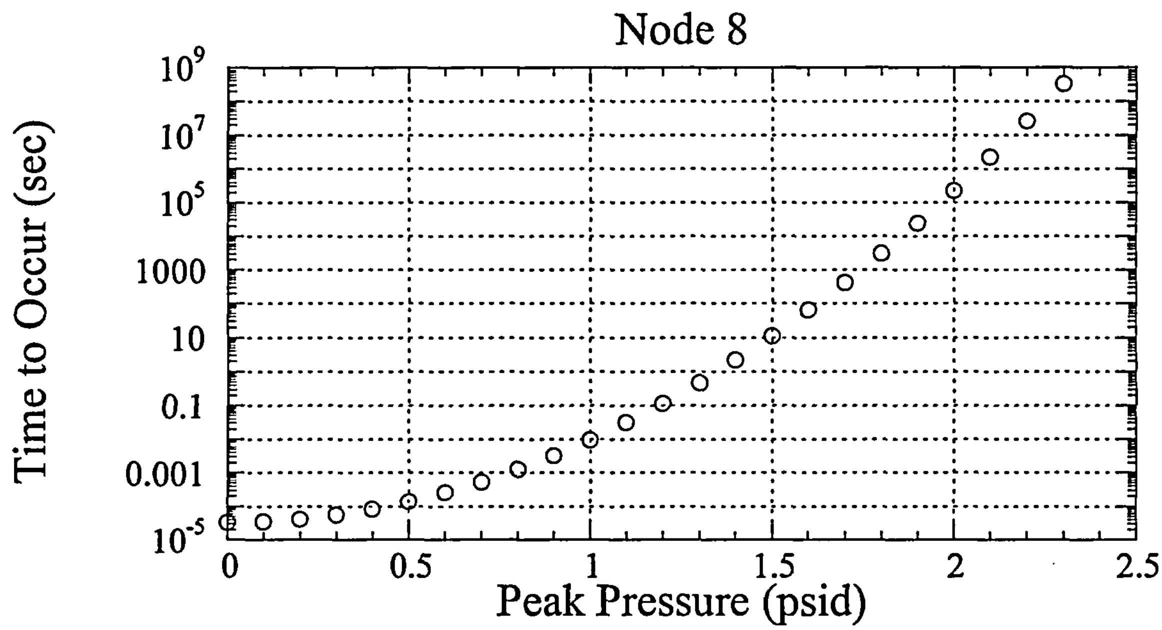


Figure 5.1. Probability density functions for predicted pressures at node 8 (top) and node 99 (bottom).



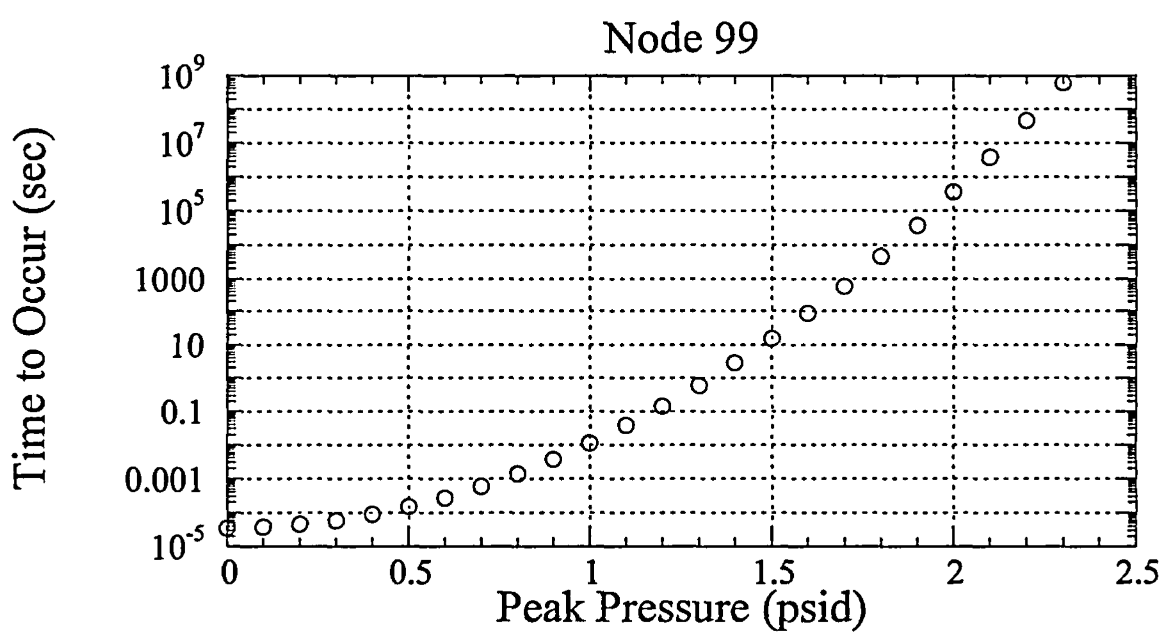
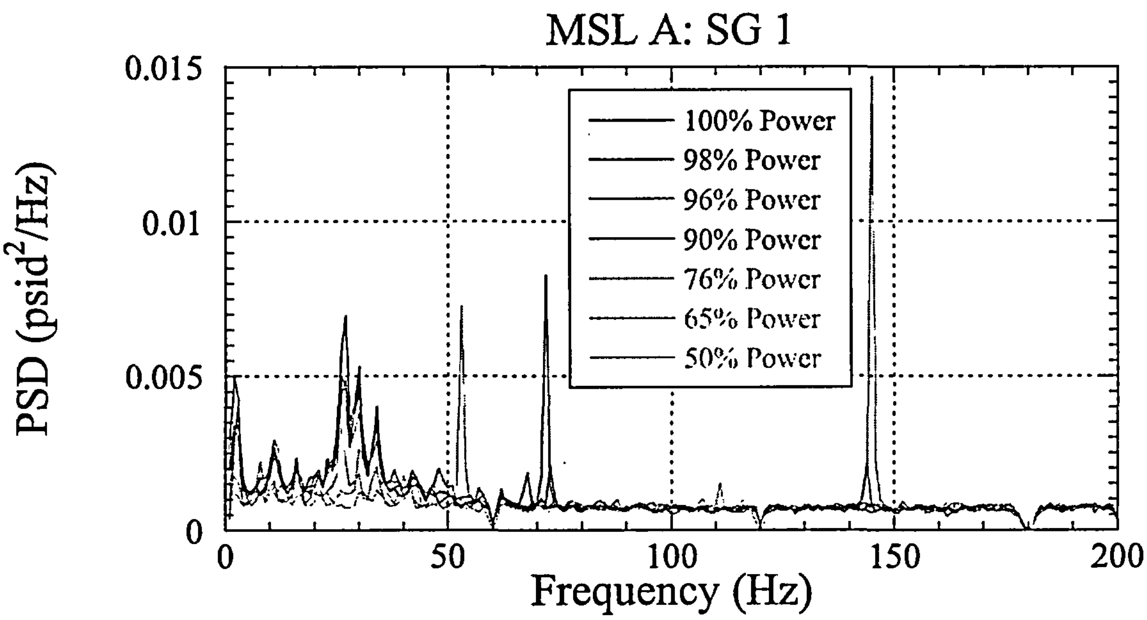


Figure 5.2. Peak pressure load exceedance for predicted pressures at node 8 (top) and node 99 (bottom). Typical times: 1 hour = 3,600 sec; 1 day = 86,400 sec; 1 month = 2.6×10^6 sec; 1 year = 3.15×10^7 sec; 31.7 years = 10^9 sec.

VI. Power Level Behavior

As discussed previously, additional strain gage / pressure data were supplied by PSEG at lower power levels, so that predictions could be made of the behavior of peak load on the dryer. Figure 6.1 illustrates the behavior of the PSD at a function of power level, for each of the eight strain gages. Calculations at all power levels give the pressure and RMS comparisons shown in Figure 6.2. The strain gage data (summarized in Table 3.3) show that peak strains occur in the main steam lines at 96% power. However, the acoustic circuit analysis shows that steam dryer load at one position on the dryer (node 99) is actually peak at 98% power (as shown in Figure 6.2). Rev 1



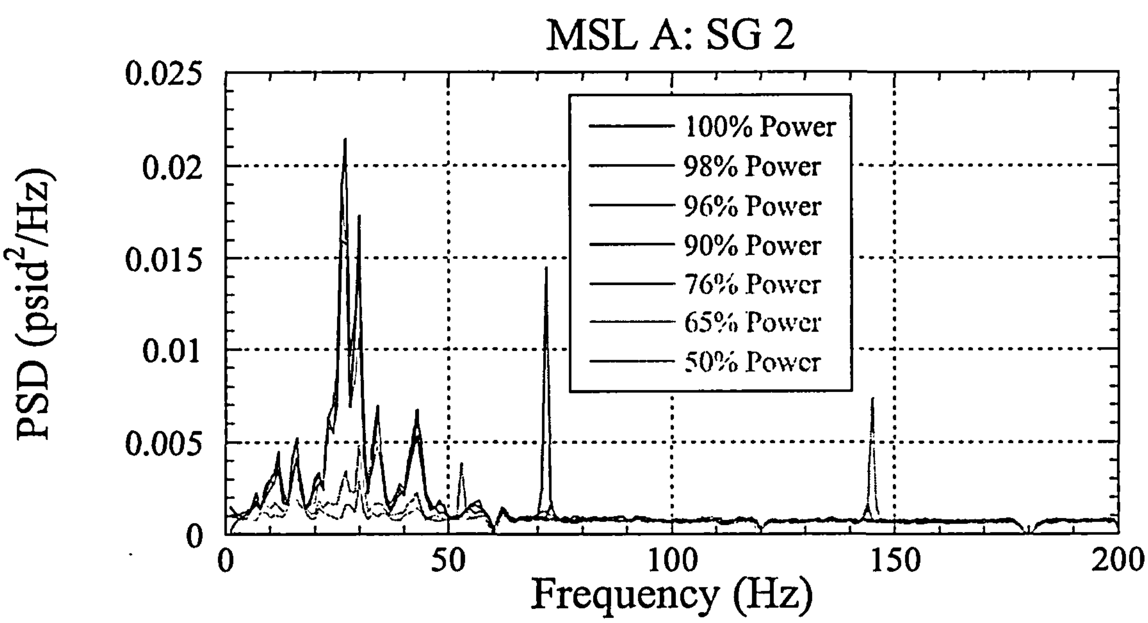
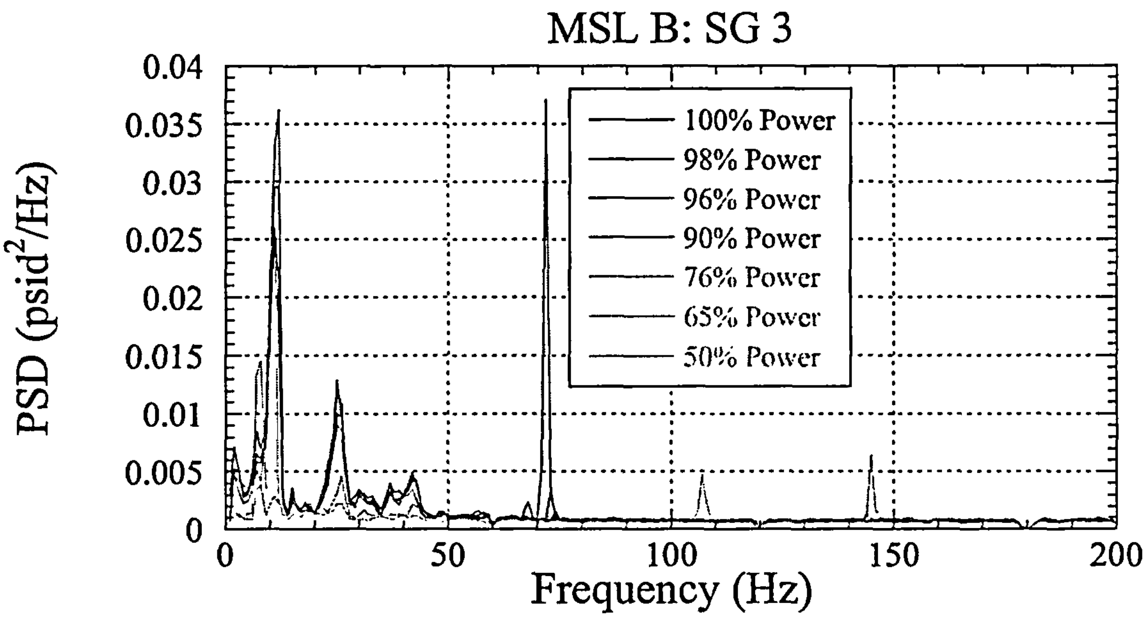


Figure 6.1a. PSD of strain gage / pressure data at strain gage 1 (top) and strain gage 2 (bottom). Frequency peaks above 50 Hz are consistent with the ERV standpipes. The seven colors represent the seven power levels examined. Frequency content at 60, 120, and 180 Hz has been filtered. The noise floor has not been removed.



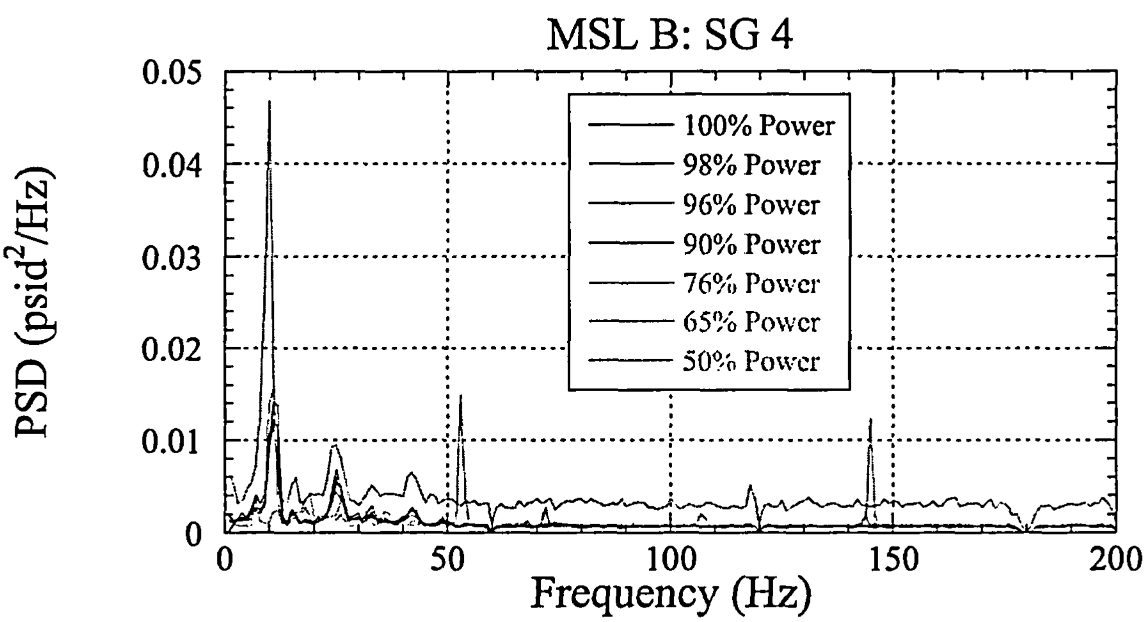
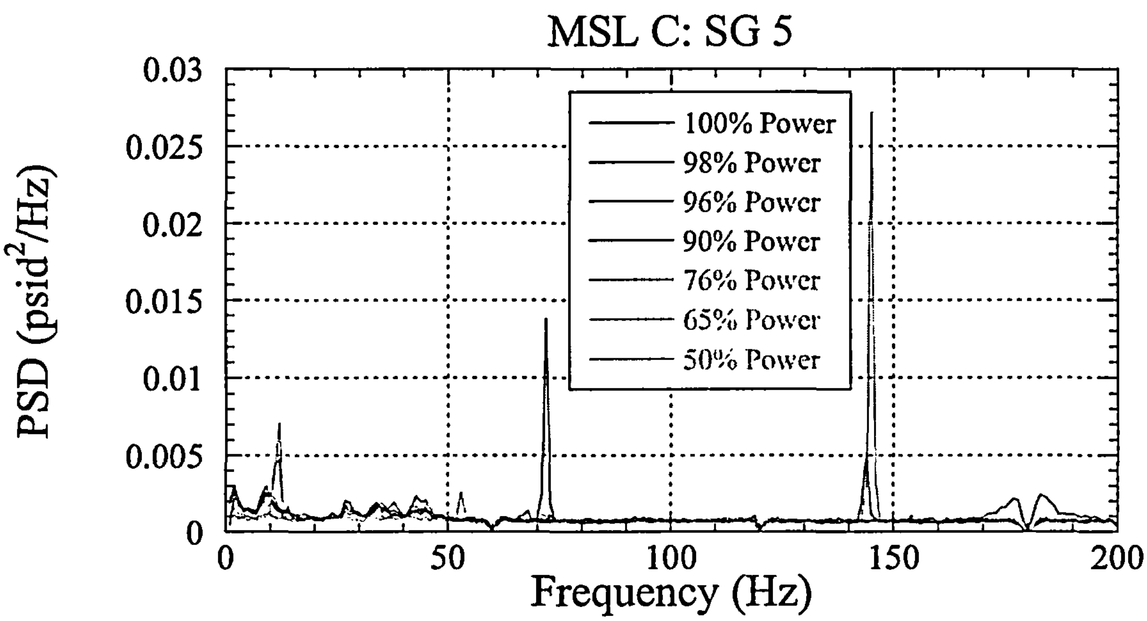


Figure 6.1b. PSD of strain gage / pressure data at strain gage 3 (top) and strain gage 4 (bottom). Frequency peaks above 50 Hz are consistent with the ERV standpipes. The seven colors represent the seven power levels examined. Frequency content at 60, 120, and 180 Hz has been filtered. The noise floor has not been removed.



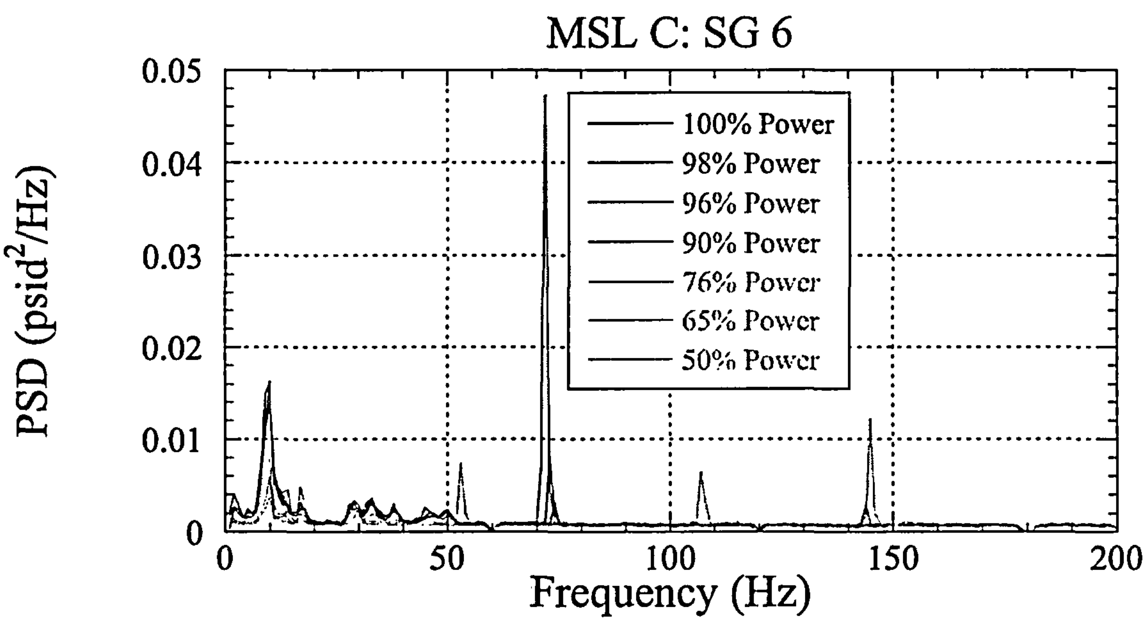
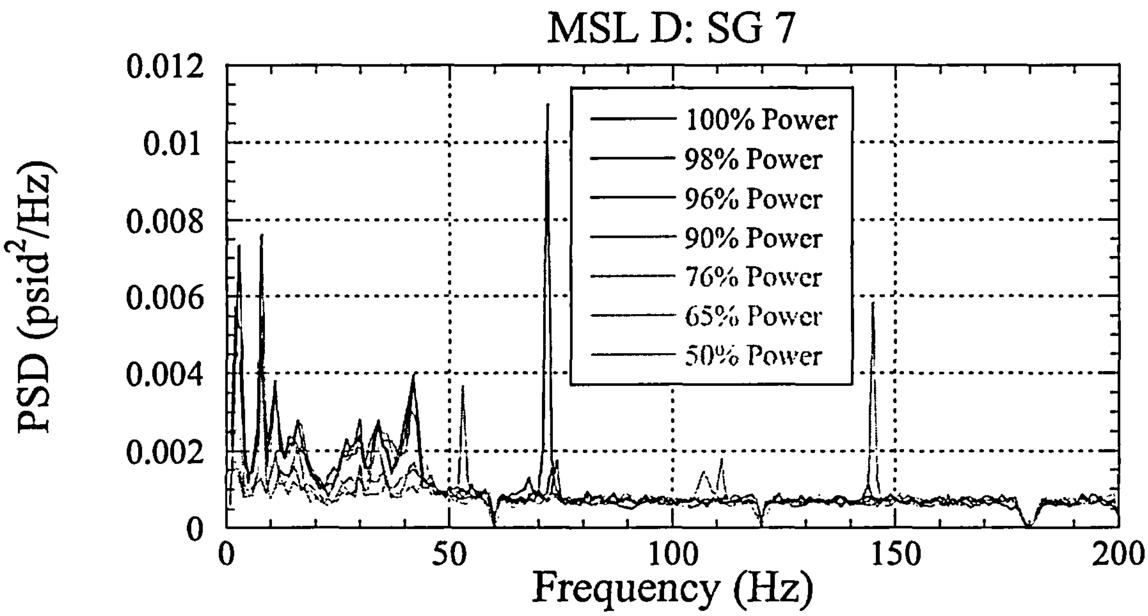


Figure 6.1c. PSD of strain gage / pressure data at strain gage 5 (top) and strain gage 6 (bottom). Frequency peaks above 50 Hz are consistent with the ERV standpipes. The seven colors represent the seven power levels examined. Frequency content at 60, 120, and 180 Hz has been filtered. The noise floor has not been removed.



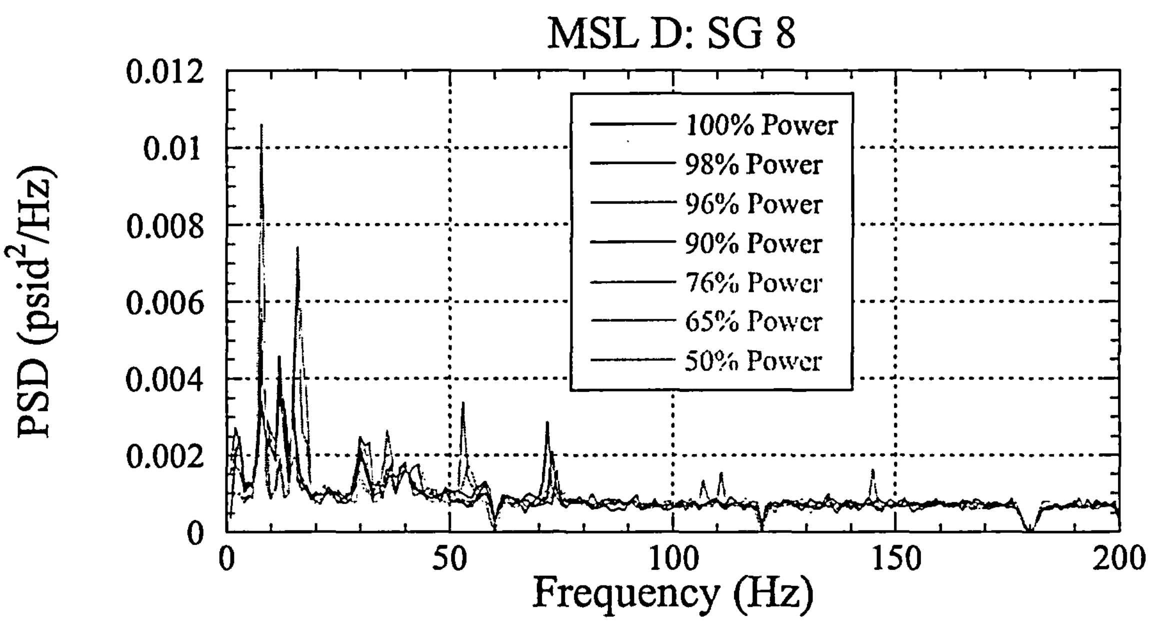


Figure 6.1d. PSD of strain gage / pressure data at strain gage 7 (top) and strain gage 8 (bottom). Frequency peaks above 50 Hz are consistent with the ERV standpipes. The seven colors represent the seven power levels examined. Frequency content at 60, 120, and 180 Hz has been filtered. The noise floor has not been removed.

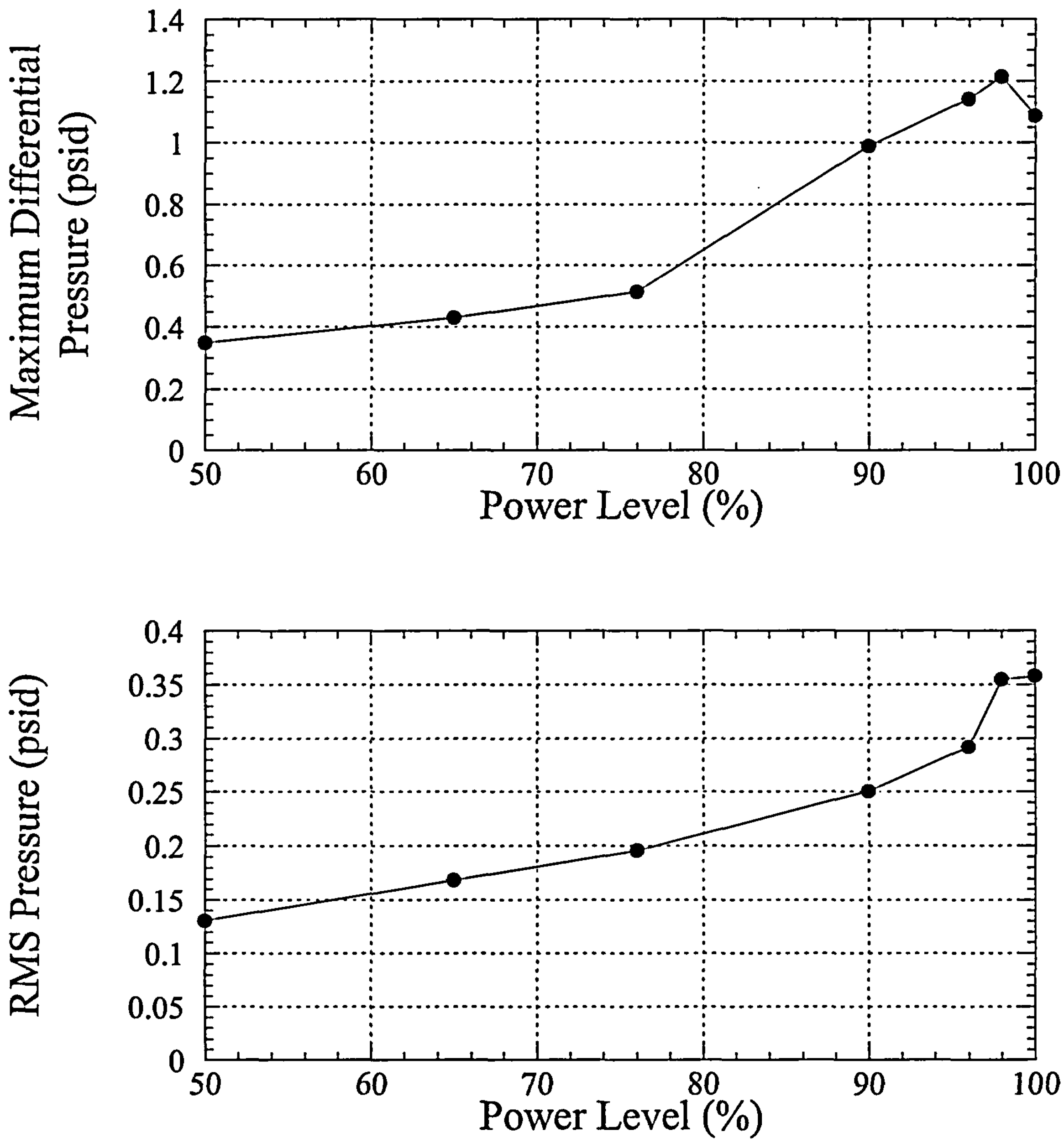


Figure 6.2. Summary of maximum differential pressure (top) and RMS pressure (bottom) as a function of power level in HC1.

VII. Error Analysis

The analysis of potential uncertainty occurring at HC1 consists of two contributions: the uncertainty when using a single strain gage at each location with the acoustic circuit methodology, and the uncertainty with respect to position of these strain gages relative to the strain gages at QC1 and QC2.

Through an extensive analysis, Exelon [6] concluded that the best estimate of the overall uncertainty for steam dryer acoustic circuit analysis methodology was that the error would range from a maximum under prediction of 3.5% to a maximum over prediction of 14.5%. These estimates are based on the use of strain gage pairs positioned on the four main steam lines at approximately 10 and 40 feet downstream of the steam dome. However, in a recent report [4], Structural Integrity Associates argued that there is conservatism built into the data collected at the single strain gages in Hope Creek, as compared against the data collected from strain gage pairs as was done at Quad Cities. SIA suggests that this conservatism is bounded by a factor of between 1.16 and 2.40 [4]. It is suggested that no credit be taken for conservatism in the number of strain gages by Hope Creek at this time.

The second uncertainty arises from the actual locations of the strain gage pairs at Hope Creek. In a similar analysis for Vermont Yankee [7], it was concluded that an average error of 42.1% is possible if the main steam line data collection locations are farther downstream than on Quad Cities. Since no credit was taken for the number of strain gages used, it is suggested that 42.1% be used for the uncertainty in the strain gage locations. Thus, an SRSS of the two uncertainties (an average of 8.0% from the Exelon analysis and 42.1% from the Vermont Yankee analysis, or 42.9%) is sufficient to bound all uncertainties that exist in this analysis, until such time that strain gage pairs can be repositioned and installed closer to the steam dome, as was done in Quad Cities.

VIII. Conclusions

The C.D.I. acoustic circuit analysis, using in-plant measured data from HC1

a) Determines that steam dryer differential hydrodynamic loads at 96% power are less than 1.2 psid.

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 highest differential pressure load on the dryer occurs at 72 Hz.

The following additional work is suggested:

- It is highly recommended that strain gages be positioned much closer to the steam dryer. This method has been used successfully by Exelon, and load uncertainty levels of less than 10% have been achieved.

IX. References

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3. Structural Integrity Associates, Inc. Letter Reports. "Hope Creek Strain Gage Data" (14 July 2005) and "Hope Creek February 2005 Strain Gage Data – ASCII Files" (01 August 2005).

4. Structural Integrity Associates, Inc. Letter Report. "Hope Creek Steam Dryer Hydrodynamic Loads Assessment" (11 October 2005). SIA Report No. SIR-05-258 Revision B.

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6. Exelon Nuclear Generating LLC. 2005. An Assessment of the Effects of Uncertainty in the Application of Acoustic Circuit Model Predictions to the Calculation of Stresses in the Replacement Quad Cities Units 1 and 2 Steam Dryers (Revision 0). Document No. AM-21005-008.

7. Continuum Dynamics, Inc. 2005. Vermont Yankee Instrument Position Uncertainty. Letter Report Dated 01 August 2005.