ENCLOSURE 2

Attachment 5

Exelon Report Number AM-2005-008, "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, dated August 19, 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

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Nuclear Engineering Department
Exelon Nuclear Generating Co.

Prepared by: Kevin Ramsden Date: 8/19/05

Reviewed by: Guy DeBoo Date: 8/19/05

Concurred by: Alan Bilanin CDI Date: 8/19/05

Concurred by: GE Date: 8/19/05

Approved by: Roman Gesior Date: 8/19/05
(Date Issued)

Abstract

This report documents the evaluation of uncertainties associated with the prediction and application of unsteady loads to the Quad Cities Units 1 and 2 steam dryers. Elements of the overall uncertainty have been determined and discussed individually in previous reports and calculations. The intent of this report is to compile the various components contributing to the overall uncertainty and provide an assessment of the net uncertainty effects for the evaluation of steam dryers subjected to unsteady pressure loads.

1. Introduction

This report documents the evaluation of the uncertainty associated with the prediction and application of unsteady pressure loads on the Quad Cities (QC) Units 1 and 2 steam dryers. The Continuum Dynamics, Inc. (CDI) Acoustic Circuit Model (ACM) takes inputs from Main Steam Line (MSL) mounted strain gages and provides a detailed pressure time history for the steam volume of the reactor pressure vessel, with emphasis on the surfaces of the steam dryer. This methodology has been validated against in-plant measurements taken on the QC 2 instrumented steam dryer during power ascension testing. The output of the ACM is used as input to the General Electric (GE) Finite Element Model (FEM), which is used to compute the stresses in the dryer for comparison against code allowable fatigue and stress limits.

Due to the complicated nature of the issue, this process has the possibility to be affected by uncertainties in a number of ways:

1) Measurement accuracy of the strain gages
2) Accuracy of the ACM itself
3) Measurement accuracy of the in-situ QC 2 pressure measurements used for validation of the ACM
4) Accuracy of the FEM

This report examines the individual components of uncertainty, then develops a recommendation for the treatment of uncertainty in the integrated application. The intent is to form a basis for the QC1 and QC2 applications, as well as for future applications of this methodology for the Dresden Unit 2 and Unit 3 steam dryers.

2. Description of Uncertainties

The individual parts of the application will be discussed.

2.1 Strain Gage Measurements

There are two key elements that apply to the results obtained from strain gages to determine breathing mode unsteady pressures for use in the ACM. The first concerns the ability of the strain gage to read the strain measurement correctly and to process the strain measurement into a pressure term. The second involves the potential for strain gage measurements to include local pipe structural response, e.g., bending mode not directly related to internal pressure, in addition to the breathing mode response.

2.1.1 Strain Gage Measurement Accuracy

The MSL pipe strain gage measurement uncertainty is composed of two major components. These are the instrumentation, cabling and data acquisition response and the conversion of hoop strain to pressure, i.e., the wall thickness of the pipe. To minimize uncertainty and yield the most accurate predictions possible, ultrasonic measurements were made of the QC1 and QC2 MSLs at the strain gage locations. Reference 1 provides an assessment of the strain gage measurement accuracy. A value of 5.02% was determined to be the accuracy of the strain gage measurements.

In Reference 2, the error in strain gage readings was applied to the eight sets of strain gage data used to develop the unsteady pressure input into the ACM. The changes in pressure in the four dryer pressure transducers closest to the steam line nozzles was then computed to determine the uncertainty in the minimum error ACM predictions due to strain gage uncertainty. The pressure predictions were determined to be accurate to within +/-3.6%.

2.1.2 Pipe Structural Response Effects on Strain Gages

The underlying premise of using strain gages to measure unsteady pressures in the MSL pipes is the ability to determine the breathing mode (hoop) component of strain and use simple relationships to infer the unsteady internal pressure. Experience with testing at QC2 demonstrated that two perpendicular pairs of strain gages in combination yield more accurate results than a single pair. [Reference 3.] In addition, differences in amplitudes are noted when the strain gage pairs are located in-plane with piping elbows versus out of plane. Both of these effects were noted while processing QC2 790 megawatt-electric (MWe) data. With a single pair of strain gages, introduction of non-acoustic signals was observed, particularly near 80 Hz, which was negated when the second pair of strain gages was combined.

The QC2 steam path was fully instrumented to support the development of loads on the steam dryer based on pressures derived from MSL strain gage data and the use of an ACM. The in-vessel pressure detectors mounted on the QC2 dryer supported the validation of the overall methodology. The QC1 steam path contained MSL strain gages only, supplemented by steam system dynamic pressure measurements taken at selected locations. The failure of some strain gages on QC1 occurred prior to establishment of the steam dryer loads for QC1. Therefore, it is important to understand the implications of loss of strain gages on the establishment of a load definition on the steam dryer. In the work presented in Reference 3, it was shown that pressure calculations based on three strain gages provide very similar results to four strain gage combinations. With three gage combinations, some adjustment at frequencies near 80 Hz is still necessary to approach the four gage pressure prediction.

2.2 QC2 Steam Dryer Pressure Measurement Uncertainty

The uncertainty in dryer pressure measurements consists of two components. The first is the instrument accuracy and calibration results. The second is due to phenomenological effects that may induce error into the steam dryer-mounted pressure instruments.

2.2.1 Instrument Accuracy

Reference 4 provides a detailed discussion of the expected instrument accuracy based on vendor supplied data and calibration results. The testing used two instrument types with differing ranges for each. Two of the instruments used a larger range and had a slightly higher absolute error. The remaining 25 were of a smaller range and had a lower absolute error. The instrument accuracy is developed for both and yields a 3.9% absolute measurement uncertainty and a 2.9% relative measurement uncertainty for the limiting sensor. The relative measurement uncertainty is the most appropriate value to apply for this assessment, since variations from the mean are of interest, rather than the absolute maximum values.

2.2.2 Phenomenological Considerations

There are phenomenological considerations that are salient to the unsteady pressure measurements taken on the QC2 steam dryer. These include:

1) The effects of dome-mounted versus flush-mounted pressure transducers, with respect to measurement of incident acoustic pressure oscillations.
2) The potential for the nozzle entry vortices to induce unsteady velocity fields on the sensors nearest the nozzles.

Item 1 was the subject of considerable analytical work, as well as confirmatory testing in a wind tunnel. The results of this work are contained in Reference 5. There were two important conclusions of this work:

1) The dome-mounted sensors will tend to overpredict the pressures by 3-8%. No correction was recommended in the test data reduction since the overprediction is conservative in application to structural analysis considerations.
2) The sensor domes had an extremely low sound signature as determined by wind tunnel testing. Therefore, the sensor domes could reasonably be expected to yield appropriate frequency content, unaltered by bluff body acoustic noise from the housing. It was also determined that downstream sensors would not be affected by vortex shedding from upstream sensor mounts.

Item 2 is addressed in Appendix A of this report. Based on review of the data collected on QC2, it was determined that there is no need to add a factor to the sensors opposite the steam nozzles to account for uncertainty in dynamic effects.

2.3 Uncertainty Associated with the ACM

The validation of the ACM has been performed against QC2 in-vessel measurements. The initial efforts were directed at comparison predictions to measurements at six sensor locations. Two blind benchmark tests were performed and subsequent model adjustments were made. The resultant model, typically referred to as the "modified 930 MWe model," was then applied to develop dryer loads that were used to qualify the QC2 steam dryer. In this work, it was noted that the model generally overpredicted the loads, particularly in the steam dryer skirt region. The frequency content was found to be accurate, particularly at the dominant acoustic load frequencies (135-160 Hz). This validation is provided in Reference 6.

Recognizing that the ACM validation had been performed for a limited number of sensor locations, and had the tendency to overpredict the loads in the skirt region, an effort was initiated to revise the ACM and perform validation over a larger set of pressure measurements. Specifically, a revised Helmholtz solution was implemented for the vessel that featured more physically representative boundary conditions in the skirt region. In addition, a least squares method was used to adjust the model damping to provide the minimum error for the full set of pressure sensors. Validation of this minimum error ACM was performed by CDI as documented in Reference 2.

Exelon performed additional validation work on the minimum error ACM comparison to test data. The Exelon study (i.e., Reference 7) focused on an assessment of the CDI ACM with respect to the distribution of peak loads.

Statistical evaluations demonstrated that the minimum error model captures sufficient amounts of the pressure distribution to be representative and appropriate for design evaluation without the need for additional multipliers. Specifically, it was concluded that the model was capable of meeting 95-95 criteria on all external surfaces of the steam dryer, with two exceptions; these exceptions would meet 95-90 criteria. It is important to note that the statistical treatments performed, and the associated results, are valid only for the application stated, which is to provide appropriate peak-to-peak pressure response for input to a structural model. Use of the ACM for other applications would require additional evaluation.

2.4 Structural Model Uncertainty

The structural Finite Element Analysis (FEA) model is based on detailed as-built steam dryer geometry. A specific analytical uncertainty associated with the FEA calculation has not been determined, largely because of the complexity of the model. To minimize this uncertainty, separate finite element models of the dryer were independently developed and subjected to identical pressure time histories. Comparing the finite element analysis results, showed both models predicted similar stress analysis results for critical components such as the outer hoods. For design purposes the model producing the more conservative results was used to predict the dryer stresses. Sensitivity analyses were performed by varying the time step by +/- 10%. This interval selection was based on review of the results of the hammer testing performed on the Unit 2 replacement dryer. This sensitivity covers the potential for uncertainty in the structural frequency of the model and the dynamic amplification that would be experienced if a loading frequency approached a structural frequency. The highest responses from the three runs are used to conservatively assess the dryer. To provide additional accuracy, component finite element models constructed with 3 dimensional, solid elements were used to evaluate those dryer components that were not conservatively represented by shell elements in the full dryer model. In addition, steam dryer component critical damping has been verified by in-vessel measurements and by hammer tests to confirm reasonable and conservative damping was considered in the finite element analyses. [References 8 and 9.] These additional models and analyses address the potential uncertainties in the finite element analyses and provide reasonable assurance that the stresses calculated are conservative.

3. Calculations/Data Considerations

3.1 Software Applications

The Mathcad-11 software package was used to support this evaluation. The statistical analysis features were used to calculate standard deviation (rms pressure) along with minimum, maximum, and mean values. The spectral analyses presented were performed using complex Fast Fourier Transforms, to allow characterization of the frequency content and power spectral density (PSD) of the measured data. The data sets were reviewed to determine the data trigger point. All data after the trigger point was used from each data set. The PSDs were generated using sample groups of 2048 samples per group, based on the data time step.

3.2 Comparison of Modified 930 MWe ACM to Minimum Error ACM Predictions

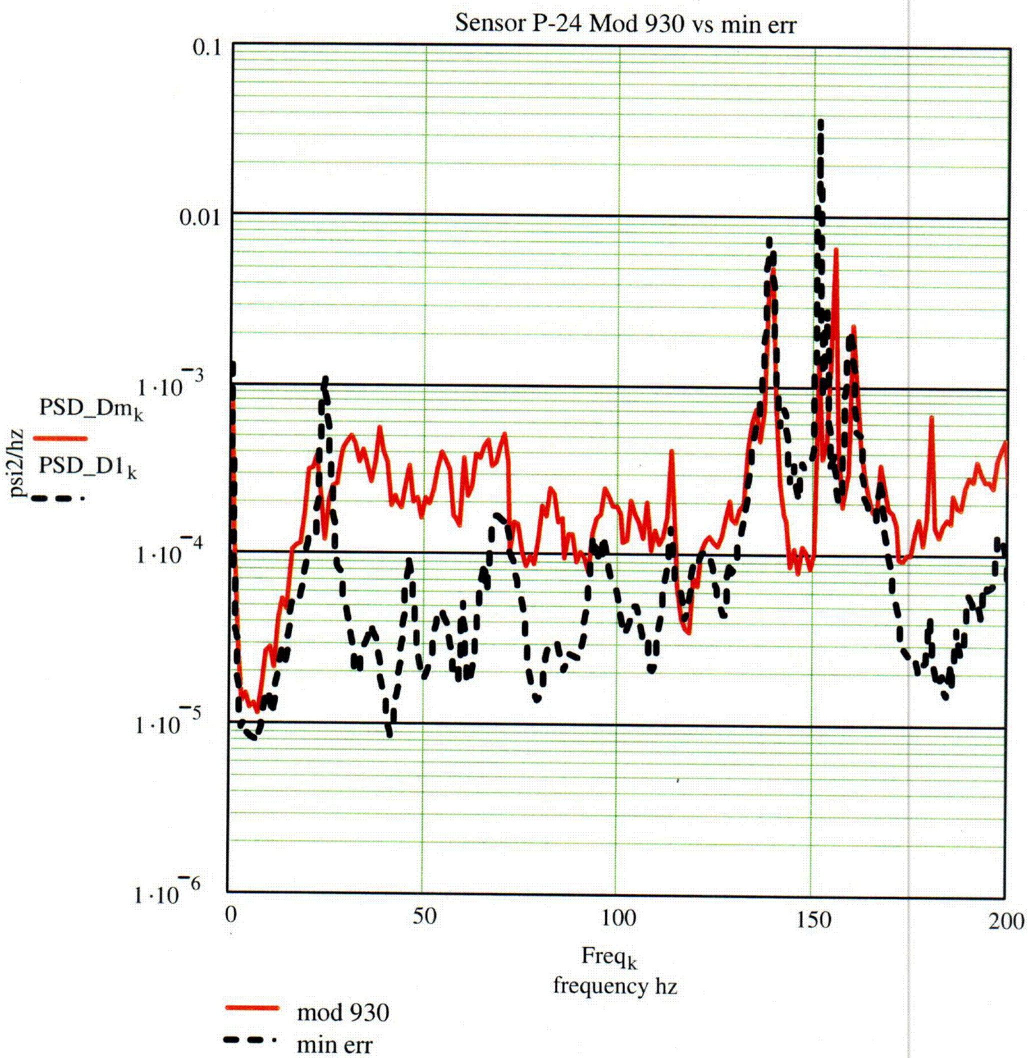
Comparison of the modified 930 MWe ACM results to the minimum error ACM results for QC2 test data is provided in the following table, based on data calculated in References 6 and 7.

Table 1 Statistical Comparison of Minimum Error and Modified 930 MWe ACM

Sensor	*RMS pressure psi*	*Min pressure psi*	*Max pressure psi*
P-3 min err	0.603	-1.894	1.971
P-3 mod 930	0.682	-2.262	2.193
P-12 min err	0.625	-1.94	1.906
P-12 mod 930	0.659	-1.751	1.848
P-20 min err	0.541	-1.648	1.738
P-20 mod 930	0.605	-1.977	1.994
P-21 min err	0.638	-1.974	2.026
P-21 mod 930	0.804	-2.289	2.337
P-24 min err	0.288	-1.129	1.016
P-24 mod 930	0.251	-1.034	0.986

The data above demonstrates that the modified 930 MWe ACM generally overpredicts both RMS and peak values compared to the minimum error ACM results. It can be readily seen that the peak values in the 930 MWe ACM are greater than 1.96 times the RMS. This suggests that the modified 930 MWe ACM provides comparable capture of the peak pressure distribution as the minimum error ACM. What is not apparent is why the skirt sensor location P-24 is more conservative in the modified 930 MWe ACM than the minimum error ACM. The reasons for this are subtle, and depend more on the frequency content of the load than on the absolute magnitude. In addition, the skirt is more responsive to low frequency loads. The following figure compares the predicted frequency content of the modified 930 MWe ACM and the minimum error ACMs for the P-24 skirt location.

Figure 1 PSD of Load Predictions at P-24



The figure illustrates that the minimum error load prediction produces significantly less frequency content in the 30-120 Hz range. This is a direct consequence of the refined Helmholtz solution employed in the minimum error load set, and explains why the modified 930 MWe ACM produces higher predicted skirt response.

3.3 Strain Gage Failure Considerations

As noted in Section 2, the failure of strain gages can have a considerable impact on the resulting pipe internal pressures used as input to the ACM. Specifically, the loss of strain gages tends to cause over-prediction of pressures and also to introduce non-acoustic frequency content due to non-breathing mode piping structural responses. Reference 10 investigated the effects of strain gage failure on QC1 and documented comparisons to calculated single pair response on Unit 2. The conclusion that can be drawn is that loss of in-plane strain gages, particularly at the 651' elevation can have dramatic effects on the predicted pressure and frequency content. Subsequent efforts to include the remaining strain gage into the pressure calculation have been performed, along with selected adjustment of 80 Hz (approximate) signal content. [Reference 3] This was performed in a manner that will overpredict the response applied to the ACM.

4. Results

Based on the discussion in Sections 2 and 3, an overall assessment of uncertainties and conservative applications was generated. Separate tables are provided for each unit to reflect differences in the analysis. The uncertainty summaries are contained in the following tables.

Table 2 Uncertainty Terms in Unit 1 Dryer Analysis

Uncertainty Term	*Absolute Effect %*	*Effect on Analysis*
Strain Gage Measurement	5.02	+/- 3.6% based on minimum error model sensitivity
Strain Gage Failure Impact	In-plane failures yield conservative pressure predictions	Conservative results occur (magnitude and frequency content)
Pressure Sensor Measurement	3.9 Absolute 2.9 Relative	+/- 2.9%
Pressure Sensor Phenomenological	N/A	+3 to +8%
ACM Uncertainty		ACM captures 95% of peak-peak pressure distribution with high confidence levels (95%)
Structural FEA		Bounding values selected based on +/- 10% time step sensitivity cases, plus other attributes of FEA noted in section 2.4.
Net Effect		Range: underpredict by 3.5% to overpredict by 14.5% plus conservatism introduced by strain gage failure, and use of modified 930 MWe ACM for upper dryer loads

Table 3 Uncertainty Terms in Unit 2 Dryer Analysis

Uncertainty Term	*Absolute Effect %*	*Effect on Analysis*
Strain Gage Measurement	5.02	+/- 3.6% based on minimum error model sensitivity
Strain Gage Failure Impact	N/A	N/A
Pressure Sensor Measurement	3.9 Absolute 2.9 Relative	+/- 2.9%
Pressure Sensor Phenomenological	N/A	+3 to +8%
ACM Uncertainty		Modified 930 MWe ACM used for Unit 2 analysis is conservative compared to minimum error model, particularly in skirt region and front hood
Structural FEA		Bounding values selected based on +/-10% time step sensitivity cases, plus other attributes of FEA noted in section 2.4
Net Effect		Range: underpredict by 3.5% to overpredict by 14.5% plus conservatism introduced by use of modified 930 MWe ACM

5. Conclusions/Discussion

A summary of the key uncertainties and deliberate conservatism included in QC1 and QC2 steam dryer analyses was prepared. The following conclusions are made based on this work.

1) The best estimate of the overall uncertainty for dryer analysis methodology is that it would range from a maximum under-prediction of 3.5% to an over-prediction of 14.5%.
2) This uncertainty is supplemented by conservatism in the application of the ACM. For QC1, the effect of strain gage failure yields conservative load development. For QC2, the modified 930 MWe ACM produces conservative load predictions when compared to the minimum error ACM.
3) The results of the analyses for both units are conservative as currently developed. The conservatism in the load development compared with the maximum under-prediction anticipated, provides confidence in the analyses as being appropriate for validation of the structural margin of the steam dryers in both Quad Cities units.
4) The application of these methods to other plants will require careful examination of the key inputs. The uncertainty associated with the test instrumentation and model validation can be expected to remain applicable. The quality of the information (i.e., from MSL strain gages) used as input to the ACM is a key contributor to the overall determination of conservatism.

Based on the development and consideration of uncertainties presented, no additional factors are required to compensate for potential uncertainties in the various elements of the replacement steam dryer evaluation.

6. References

1. Structural Integrity Associates, Inc. 2005. Quad Cities Strain Gage Evaluation. Calculation Package File No. EXLN-20Q-301, Project No. EXLN-20Q. Revision 0.
2. C.D.I. Report No. 05-10 - Benchmarking of Continuum Dynamics, Inc. Steam Dryer Load Methodology Against Quad Cities Unit 2 In-Plant Data, Revision 0.
3. SIA letter report, SIR-05-223 Revision 1, "Comparison of Quad Cities Unit 1 and Quad Cities Unit 2 Main Steam Line Strain Gage Data," July 18, 2005.
4. GE-NE-0000-0037-1951-01, Revision 0, "Dryer Vibration Instrumentation Uncertainty," April, 2005.
5. GE-NE-0000-0038-2076-01-Revision 0, Summary of the Effects of the Sensor Cover Plates on Dynamic Pressure Measurement," April, 2005.
6. "Acoustic Circuit Benchmark, Quad Cities Unit 2 Instrumented Steam Path, 790 MWe and 930 MWe Power Levels," AM-2005-002, June 2005.
7. "Acoustic Circuit Model Validation, Quad Cities Unit 2 Instrumented Steam Path, Final Model Revision 930 MWe Power Level," AM-2005-004, Revision 0, July 2005.
8. GE letter report, GE-NE-0000-0039-4749, Revision 1, "Exelon Steam Dryer Replacement Program-2% Structural Damping for Seismic and Non-Seismic (FIV) Dynamic Analysis for Quad Cities 1 and 2," June 22, 2005.
9. LMS Report, "Test and Analysis Report. Quad Cities New Design Steam Dryer. Dryer #1 Experimental Modal Analysis and Correlation with Finite Element Results," Revision 1, May 12, 2005.
10. "Comparison of Acoustic Circuit Dryer Loads for Missing MS Line Strain Gauges to Acoustic Circuit Dryer Loads with All MS Line Strain Gages," AM-2005-006, Revision 0, July 2005.

Appendix A- Consideration of Dynamic Effects on Pressure Sensors Near the MSL Nozzles

Purpose

The purpose of this appendix is to document the investigation performed to assess the need for additional dynamic compensation terms on the sensors nearest the vessel steam nozzles. As noted in Reference 4, the effect of placing the pressure sensors in dome housings was anticipated to result in a conservative bias of 3 to 8% overall, compared to mounting the sensors flush with the surfaces of the steam dryer. One concern with respect to the sensors located closest to the steam nozzles was that turbulence due to vortex behavior might affect the measured pressures at these locations. The complexity of the geometry precluded simple calculation of these effects, and it was determined that the best way to address this concern would be to review the test data to identify if this behavior were evidenced.

Review Method

Turbulence near the vortex entering the steam nozzle would be expected to be fairly low frequency (i.e., below 100 Hz). The vortex itself would be expected to produce a frequency of about 20-25 Hz, based on the formulas governing vortex whistles. The review of the plant data focused on two elements that would indicate a reason for concern.

1) There would be a significant spike in the lower frequency 0-100 Hz data for sensors near the nozzles.
2) This spike would not be reflected in other sensors further from the nozzles since it is a local turbulence effect and not a propagating acoustic phenomena.

PSD plots were prepared for sensor locations P-3 and P-12 (the sensors nearest the nozzles on the 90 degree side of the dryer). Similar PSDs were generated for sensor locations P-2 and P-11, which are adjacent to P-3 and P-12, but higher up on the dryer face.

Results

The PSD plots are shown in Figures A-1 through A-4. The frequency content between P-3 and P-2 is virtually identical, as is the case for P-12 and P-11. The magnitudes are lower at P-2 and P11, which is expected. Therefore, it can be concluded that the sensors closest to the vortex are not subject to significant turbulent behaviors. As such, no correction factor is necessary to modify the sensors closest to the nozzles.

Figure A-1 PSD of Sensor P-3 Test Data 930 MWe

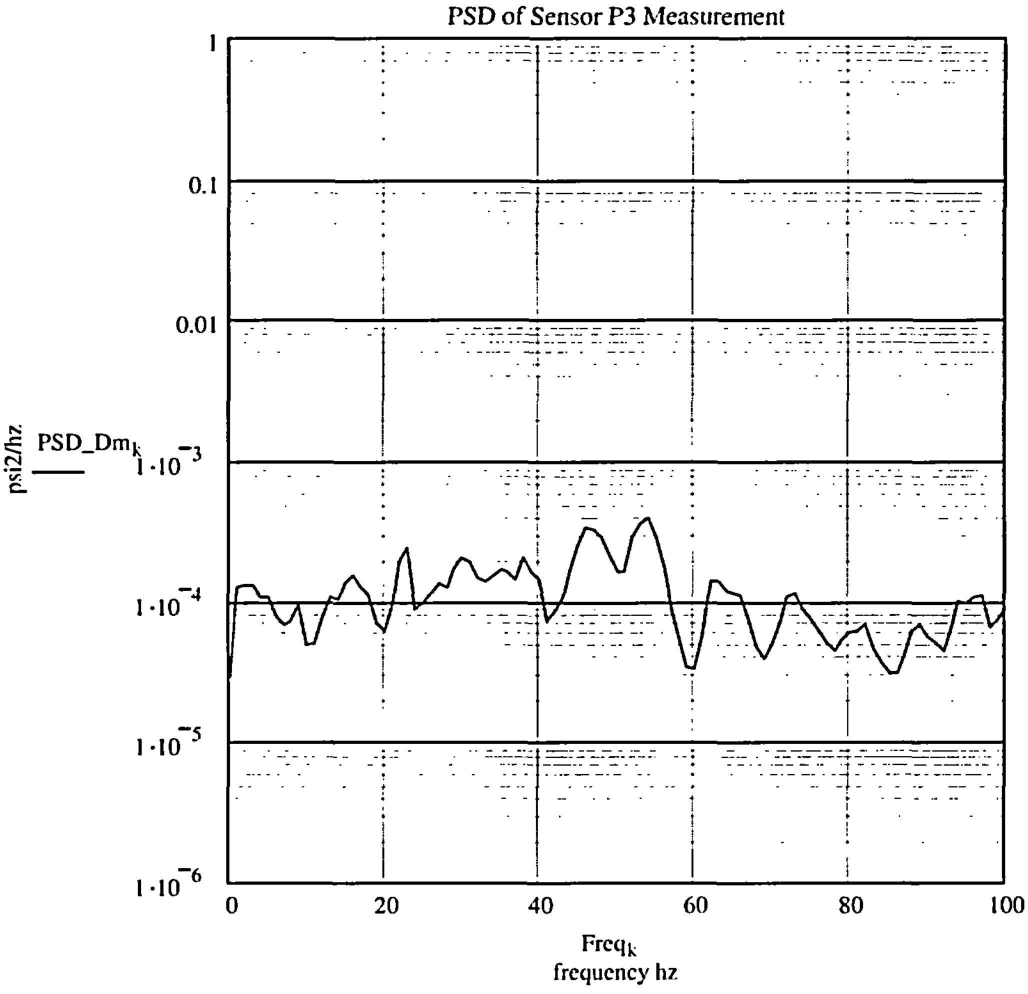


Figure A-2 PSD of Sensor P-2 Test Data 930 MWe

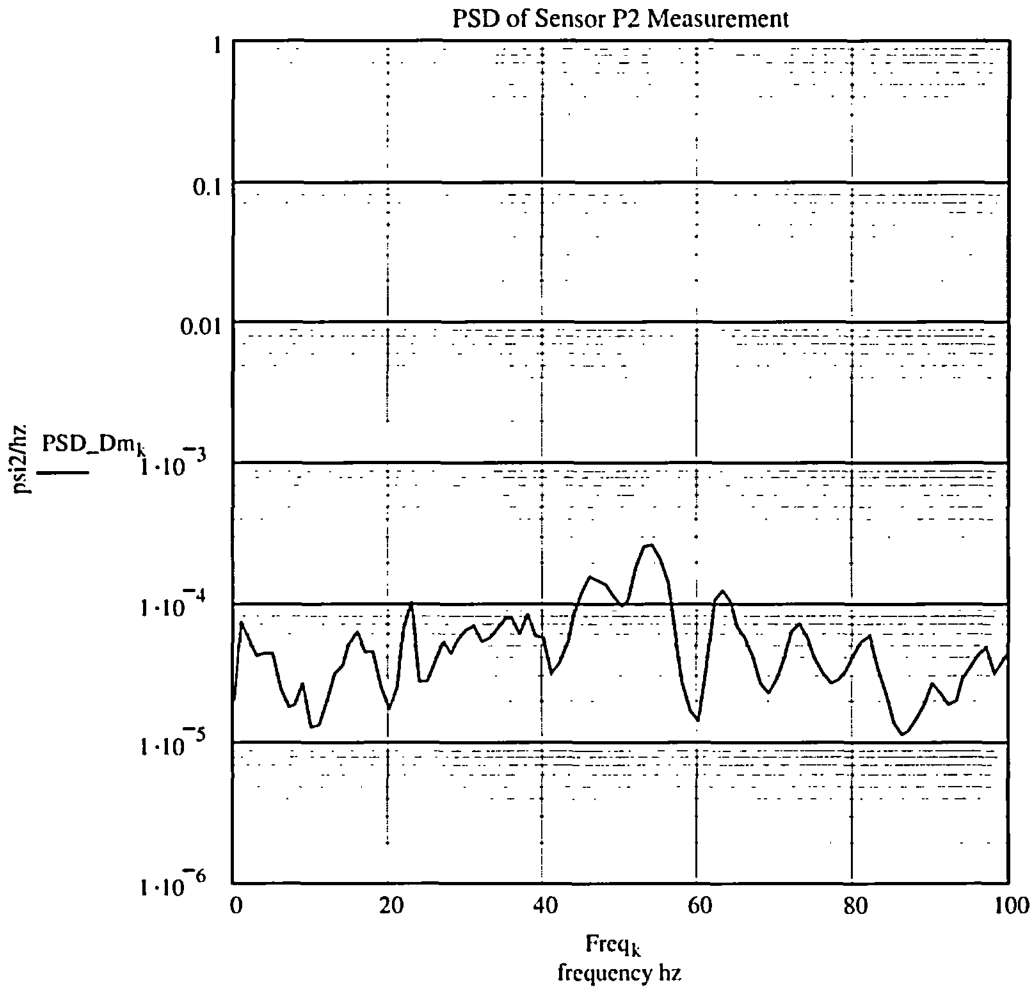


Figure A-3 PSD of Sensor P-12 Test Data 930 MWe

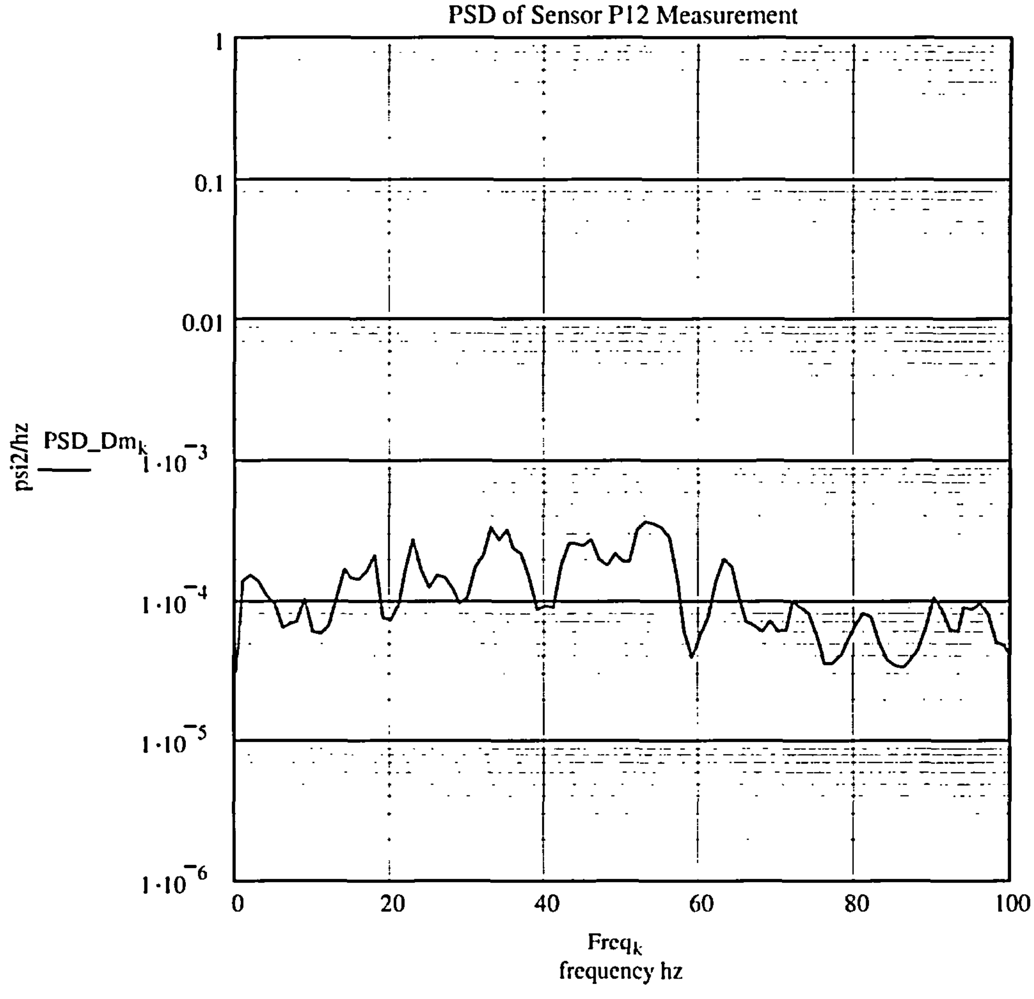


Figure A-4 PSD of Sensor P-11 Test Data 930 MWe