GE Nuclear Energy

General Electric Company
175 Curtner Avenue, San Jose, CA 95125

GE-NE-0000-0037-1951-01
Revision 0
April 2005

Exelon Corporation

Quad Cities Unit 2 Nuclear Power Plant

Dryer Vibration Instrumentation Uncertainty

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Table of Contents

List of Figures

List of Tables

GE-NE-0000-0037-1951-01
Revision 0
April 2005

QC 2 Dryer Vibration Instrumentation Uncertainty

1. Objective

Quad Cities Unit 2 is installing vibration instruments (pressure transducers, accelerometers and strain gauges) on the dryer and main steam lines to measure the dynamic loading on the dryer under rated operating conditions. The instrumentation is temporary and will be removed during the next outage. This report calculates the expected uncertainty in the measurements due to the sensors and their electronics. Any error due to disturbances caused by instrument installation is also included. However, the modeling error involved in using these measurements in the analysis (such as finite element analysis) to obtain the overall dryer loading profile is not included in this report.

2. Background

A description of the steam dryer instrumentation philosophy is given in Ref. 1, and an overall description of the instrumentation system requirements (including location of the sensors) is provided in Ref. 2. The instrument loop errors were determined by first calculating the individual loop device errors using vendor device specifications, and then combining them using the principles described in ISA standard 67.04 (Ref. 3). Where specifications are not available, engineering assumptions have been made and justifications have been provided.

3. Instrument Loop Description

The dryer instrumentation loop consists of sensors and signal and data processing electronics.

3.1 Sensors

Following is a description of the instrumentation sensors:

1) Strain Gauges (Dryer): Several (9) metallic wire strain gauges are welded on the dryer to measure the dynamic strain at the installed location on the dryer. The strain gauges will be located on the dryer skirt, drain channels, tie bar and hood. The gauges are Kyowa KHC 10 - 120 series "half bridge" configuration with a dummy resistance in the gauge Wheatstone bridge circuit for improved temperature compensation, and have been used previously in reactor environments. The sensor has a dynamic range of 5000 microstrains, however the maximum strain expected in the test is only ~ 100 microstrains. Although a dummy resistance is provided which compensates for the change in resistance of the gauge material due to temperature, there will be an apparent strain at operating temperature due to difference in thermal expansion coefficient between the gauge element material and the measurement substrate. There is also a temperature effect due lead resistances. Kyowa provides temperature compensating resistor and bridge balancing resistor to balance the gauge properly for static strain measurements. However, for the current test

application, only changes in strain (dynamic measurement) due to pressure fluctuations are of interest, so bridge balancing is not required and no correction is required for apparent strain due to temperature effects. Correction will be required due to the fact that the sensor will have a slight gap to the substrate after mounting. The sensor is a resistive gauge and has a flat response over a frequency range from 0 to 2500 Hz, so a spectrum analysis of the data can accurately provide dynamic strain at various frequencies in the range of interest (5 Hz to 400 Hz).

2) Accelerometers: Several (6) charge sensitive piezoelectric accelerometers are mounted at strategic locations on the dryer tie bars and skirt to measure dynamic dryer acceleration and displacement (by double integration of the acceleration). The accelerometers are Vibro-Meter CA 901 series with a nominal sensitivity of 10 pC/g, and have been used previously in reactor environments. These sensors can measure accelerations up to 200g, however the maximum acceleration expected in the test is only ~ 5g. The sensor frequency response is flat up to 100 Hz and increases slightly (< 5%) at 1000 Hz, so it is well suited for measurements up to the maximum frequency of interest (400 Hz). Note that the increase of sensitivity with frequency is conservative since it produces greater acceleration, but the conservatism can be removed and corrected for since the frequency response is measured and specified.

3) Pressure Transducers: A number of charge sensitive piezoelectric pressure transducers (27) are mounted at various locations on the surface of the dryer to measure dynamic pressure at these locations. The pressure transducers are Vibro-Meter CP-104 and CP-211 series, and have been used previously in reactor environments. Most (25) of the sensors are CP-104 with nominal sensitivity of 190 pC/bar, but a few (2) are CP-211 with a lower sensitivity (nominal 25 pC/bar) and the capability of measuring a larger change in pressure. These sensors have the capability of measuring dynamic pressures up to 20 bar for the high sensitivity sensor and 250 bar for the low sensitivity sensor, though the dynamic range of interest for the test is expected to be less than 0.4 bar (~ 6 psi). Some of the transmitters will be flush mounted and will not affect the steam flow path and the pressure measurement. However because of practical considerations, most will not be flush mounted and would have a domed shield over them to minimize flow disturbance, and this could disturb the dynamic pressure measurements. Corrections (which could be frequency sensitive) may need to be made on these pressure measurements based on the Wind Tunnel test data (Ref. 4). The sensor frequency response is flat from 2 Hz up to 100 Hz and increases (conservatively) slightly (< 2%) at 1000 Hz, so these sensors are well suited for measurements in the frequency range of interest (4 - 500 Hz). The sensitivity increase with frequency can be ignored, however frequency dependent changes due to domed pressure sensors will need to be considered in determining the magnitude of the dynamic (or fluctuating) pressure vs. frequency at the various dryer locations.

4) Strain Gauges (Main Steam Line): A number of metallic filament bonded strain gauges (~ 56) are welded onto the main steam lines (MSL) to measure the dynamic strain as an indirect measure of the dynamic pressure fluctuations in the steam lines.

The measurement system will determine the dynamic strain at various frequencies from which the main steam line pressure fluctuations at various frequencies can be calculated. Modeling errors that could lead to inaccuracies in the calculation of dynamic pressure from the measured dynamic strain, are not discussed in this report. The gauges are Hitec HBWAK-35 series "quarter bridge" configuration with inherent temperature compensation, and have been used previously in reactor environments. For a filament strain gauge, the gap between the sensor and substrate after mounting is small, so the correction due to the gap will be slight. This strain gauge is also a resistive gauge with a flat response over the frequency range of interest (5 Hz to 400 Hz), so a spectrum analysis of the data can accurately provide dynamic MSL strain (and indirectly dynamic MSL pressure) at various frequencies.

3.2 Electronics

There are basically two different types of electronic channels, one for the Vibro-Meter piezoelectric pressure transducers and accelerometers, the second for the Kyowa and Hitec strain gauges.

3.2.1 Pressure Transducer and Accelerometer Electronics

Following is a brief description of the Vibro-Meter pressure transducer and accelerometer electronic devices through which the sensor signal passes and which could affect the accuracy of the measurement.

1) Charge Converter: These converters are used with the piezoelectric pressure transducers and accelerometers. The charge converter used is the Vibro-Meter IPC-629-99 model, which can be interfaced directly with both the pressure transducers and the accelerometers. The converter input circuitry is fully floating which offers an effective immunity to interference from ground loops and other electromagnetic influences. Basically the charge converter converts the charge input from the sensors to a current output, and the output current is directly proportional to the input charge. The conversion is done in two stages. First it converts the electrostatic charge signal from the sensor into a low impedance current signal using a circuit with a given transfer characteristic. For the current test equipment the charge converter has two modules. One with a transfer characteristic of 50 microamps/pC characteristic to interface with CP-104 pressure transducers and CA-901 accelerometers, and the other with a transfer characteristic of 100 microamps/pC to interface with CP-211 pressure transducers. This low level current is amplified so that the low current level peak gives a 5 mA peak after the amplification. These transfer characteristics allow for determining the following peak fluctuations:

    a) CP-104 pressure transducers:
    Peak charge fluctuation = 5mA / 50μA/pC = 100 pC
    Peak pressure fluctuation = 100pC / 190pC/bar = ~ 0.5 bar = ~7 psi

    b) CA-901 accelerometers:
    Peak charge fluctuation = 5mA / 50μA/pC = 100 pC

Peak acceleration fluctuation = 100pC / 10pC/g = 10 g

c) CP-211 pressure transducers:
Peak charge fluctuation = 5mA / 100μA/pC = 50 pC
Peak pressure fluctuation = 50pC / 25pC/bar = 2 bar = ~29 psi

These peak values are sufficient to measure the expected dynamic pressure and acceleration values in the test.

2) Galvanic Separation Unit: This device is used in the accelerometer/pressure transducer instrument loops to interface the charge converter described in item 1 above to the signal processing electronics. The unit outputs a voltage signal proportional to the input current from the charge converter, and can be interfaced directly with the signal processing electronics. It also provides a high insulation voltage (4 KV) between the charge converter and the signal processing electronics, which can avoid problems (such as ground loops) due to potential differences between the measurement point and the signal processing electronics. The Galvanic Separation Unit used is the Vibro-Meter GSI-130 model.

3) Signal Processing Unit: This device provides the final signal amplification, attenuation and filtering of the vibration or dynamic pressure signals. The Signal Processing Unit used is the Vibro-Meter UVC-689 model, with sub modules SM1 and SM2. Capability is provided in SM1 for single integrating the accelerometer signal to give a velocity signal, and in SM2 for double integrating the accelerometer signal to give a signal proportional to the displacement. Output from this signal processing unit goes directly into the data acquisition system.

4) Data Acquisition System: Functionally the DAS system consists of a signal conditioner module with an analog amplifier, and a signal processor module with a A/D converter. The DAS model is LMS SCADAS III with a PQFA amplifier and a SP92-B 66 MHz digital signal processor. The signal conditioner and amplifier module has on-board programmable high-pass filters to eliminate high-energy low frequency components such as standing acoustic waves and pyro-electric shocks from accelerometers. The signal processor module provides real-time data acquisition and signal processing and high speed 24 bit A/D conversion.

3.2.2 Strain Gauge Electronics

Following is a brief description of the electronics that interface to the Kyowa strain gauges installed on the dryer and the Hitec strain gauges installed on the main steam lines. Only those electronic devices through which the sensor signal passes and which could affect the accuracy of the dynamic strain gauge measurement, are described.

1) Bridge Completion Circuit Junction Box: This is basically a passive device with resistors that complete the Wheatstone bridge circuit used for the strain gauge measurement. For the Kyowa strain gauge which has a dummy resistor for temperature compensation, a half-bridge resistor arrangement is used in the junction box for Wheatstone bridge circuit completion. For the Hitec strain gauge which has no dummy resistor, a quarter-bridge resistor arrangement is used in the junction box

to complete the Wheatstone bridge circuit. For Kyowa strain gauges, precision resistors are also provided in the Kyowa strain gauge bridge circuit for more complete temperature compensation and balancing under installed operating conditions, although full compensation is not required for dynamic strain measurements at some fixed temperature. The junction box (or bridge box) connects the sensor to the signal conditioning electronics contained in the Kyowa MCD-16A multi-conditioner electronic chassis.

2) Dynamic Strain Amplifier: This device provides a dynamic range adjustment switch and an amplifier for each sensor input. The output of the amplifier is directly proportional to the measured strain. The device also has adjustable low and high pass filters, to remove unwanted frequencies from the signal. The Dynamic strain Amplifier used for both the Kyowa and Hitec strain gauges is the Kyowa DPM-71A model.

3) Data Acquisition System: The DAS is the same for all sensors, and has been described in item 4 in Section 3.2.1.

4. Instrument Loop Uncertainty

Following is an estimate of the loop uncertainty for the pressure, acceleration and strain gauge measurement loops. Since the measured parameter depends upon the location of the sensor, the error for each sensor type is determined separately. Each sensor signal goes through several devices, so for a given sensor sensitivity, the error in the parameter measured by each sensor is a combination of the dynamic error in the response of the sensor and each of the signal conditioning devices in the sensor loop. The error calculation assumes that the sensitivity of the sensor to the parameter is known, so an important part of the error calculation is to establish the sensor sensitivity for the operating conditions, since that is not always clearly defined in the vendor data sheets. Generally a conservative estimate is desired to assure that the measured (or indicated) parameter is larger than the actual parameter.

4.1 Pressure Measurement Loop

4.1.1 Transfer Function

For this QC2 test, the pressure measurement is a measurement of the dynamic pressure as a function of time and frequency in the range of interest (~ 5 to 400 Hz). The piezoelectric sensor, which is specially designed for dynamic measurements, outputs a charge proportional to the pressure, and the change in charge is proportional to the change in pressure. Since this measurement is only concerned with dynamic changes, a reference to pressure in this section is a reference to the dynamic pressure which is the change over the static pressure, and a reference to charge is a reference to the dynamic charge which is the change over the static charge. The charge converter provides a current output directly proportional to the charge, and the galvanic separation and signal processing units provide a proportional voltage signal measured by the DAS. The overall transfer function between pressure and output voltage is linear:

The electronic transfer and amplification constants are accurately known, and verified by calibration testing. Thus, once the sensor sensitivity is established, the error in measured pressure is the square root of the sum of the squares (SRSS) of the sensor and electronic linearity errors over the dynamic range of the measurement. The SRSS method is an accepted method (Ref. 3) of combining device errors to give loop error, since the errors in the sensor and loop electronic devices are independent and random. Thus once the sensor sensitivity (S_P) is established, and the transfer function and gains of the electronic devices are known through calibration, the measured value (V) is related to the pressure (P) as follows:

$$P = V / (K1 * K2 * K3 * K4 * S_P) \qquad (1)$$

Where

K1 = Charge Converter Unit Transfer Constant (milliamps / pC)

K2 = Galvanic Separator Unit Transfer Constant (Volts / milliamp)

K3 = Signal Processing Unit Transfer Constant (Output Volts / Input Volts)

K4 = DAS Transfer Constant (Digital Output Signal / DAS Input Voltage)

V = Value of Parameter read by DAS

S_P = Sensitivity of Pressure Sensor (pC / psi)

The error in the measured pressure (dP) due to linearity error of the sensor and the random errors of the electronic devices, is as follows:

$$dP = P \{1 \pm [dE_{Press. Sensor}^2 + dE_{Electronics}^2]^{1/2} \} \qquad (2)$$

Where

$dE_{Press. Sensor}$ = Specified linearity error (%) of the pressure sensor as a fraction

$dE_{Electronics}$ = Combined (SRSS) random error (%) of the electronic devices as a fraction

4.1.2 Pressure Sensors

This section establishes the pressure sensor sensitivity at operating conditions, and specifies the dynamic sensor linearity error.

4.1.2.1. Establish Sensor Sensitivity

a) Sensitivity at Calibration Temperature (Room Temp)

The pressure sensors output a charge (picoCoulombs) per bar (or psi) of pressure, and for the sensors used in the QC2 instrumentation, the following nominal sensitivities are applicable at room temperature (23 deg C)

1) CP-104 Sensitivity (Specified, nominal) =190 pC/bar = 13.1 pC/psi (Ref. 5)

2) CP-211 Sensitivity (Specified, nominal) = 25 pC/bar = 1.724 pC/psi (Ref. 6)

However, each CP-104 sensor was calibrated separately (Ref. 7), and the calibrated sensitivities are shown in Table 1. These measured sensitivities are higher than the nominal, so the deviation is conservative. However, for more accurate evaluations it is recommended that the measured sensitivities be used.

No sensitivity data was obtained for the CP-211 sensors. So for these sensors, the nominal sensitivity value should be used, and allowance made for sensitivity variation due to manufacturing tolerances. It is expected that the tolerance will be the same for the CP-104 sensors, so it is justified to use the measured CP-104 sensitivity variation as the CP-211 sensitivity variation.

b) Sensitivity at Operating Temperature

The sensitivity of these sensors increases with temperature, as shown in Figure 1 for CP-104, and Figure 2 for CP-211.

Figure 1: Sensitivity vs. Temperature - CP-104

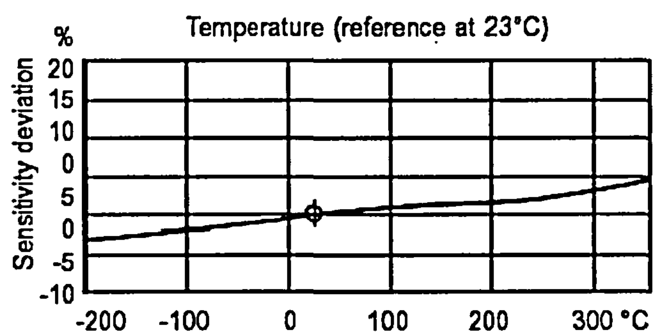
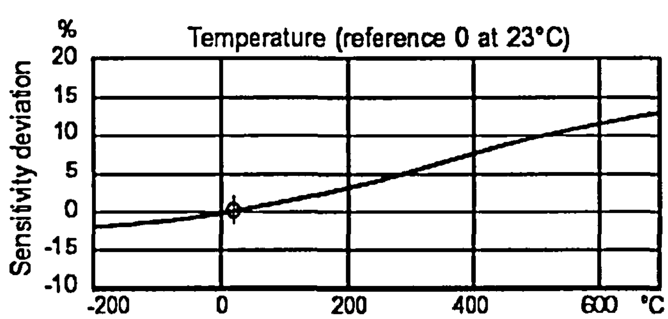


Figure 2: Sensitivity vs. Temperature - CP-211



From these figures the sensitivity increase factor for the normal operating temperature of 550 deg F is 3% for CP-104 and 5% for CP-211. For CP-104 the sensitivity increase factor was measured at 300 deg C (572 deg F) and is shown in Table 1. The average increase factor was significantly lower than the specified value, and since the increase is conservative (i.e., it produces a larger signal) and small, it is recommended that the correction factor be ignored for CP-104 if measured (less conservative than specified) sensitivities are being used. For a few cases the measured sensitivity factor was negative, and for these the sensitivity has been reduced accordingly for conservatism. So for QC2 CP-104 sensors it is recommended that the following values be used:

Sensitivity for QC2 CP-104 = See Table 1 Column 4

(No additional temperature correction required)

For CP-211, no measured data is available for either initial sensitivities or temperature reduction factors, so for these it is recommended that the following values derived from the specifications and the CP-104 sensitivity variability, be used:

Sensitivity for QC2 CP-211 at room temperature = 25 pC/bar (1.724 pC/psi)

Variability (2-sigma from CP-104 data) = 5.5%

Sensitivity Temperature Correction Factor for QC2 CP-211 = 1.04 (conservative)

Sensitivity for QC2 CP-211 at 550 deg F = 26 pC/bar (1.8 pC/psi) ± 2.6%

These sensitivity values have a justifiable basis and are considered to be conservative.

c) Radiation Effect

These piezoelectric sensors can operate in high radiation environments. According to the specifications (Ref. 5, 6) there is no effect on sensitivity up to a gamma fluence of 10^8 ergs/gm, and a fast neutron fluence of 10^{18} n/cm^2. Recent tests done by the vendor (Ref. 8) on similar pressure sensors show that there is no effect for 3 decade higher neutron fluence (up to 10^{21} n/cm^2). This is in agreement with expected performance of the sensor material (quartz) and cable insulation material (MgO), since these materials have been used in nuclear reactor environments and are known to be highly resistant to radiation degradation. Detailed calculation of the radiation levels at the sensor locations on the dryer have not been performed, however a rough (order of magnitude) calculation shows that the neutron flux at the bottom of the dryer (highest neutron flux zone) is < 10^{12} n/cm^2/sec (Ref. 9) which means that the neutron fluence level of 10^{21} will not be reached for many years. So the effect of radiation on the sensor sensitivity can be assumed to be negligible.

d) Sensor Sensitivity Drift with Time

The vendor does not specify sensor sensitivity drift with time, and has stated (Ref. 10) that based on long term tests in other applications (jet engines), the drift with time is negligible.

e) Sensor Sensitivity variation with frequency

The test procedure calls for taking time data, and then doing a spectrum analysis to determine the amplitude of pressure fluctuations at various frequencies. The frequency response is shown in Figures 3, and 4 for CP-104 and CP-211 from the vendor data sheets (Ref. 5, 6).

Figure 3: Sensitivity vs. Frequency - CP-104

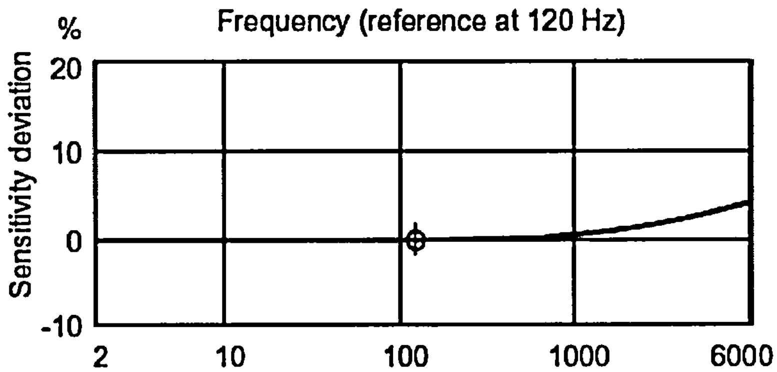
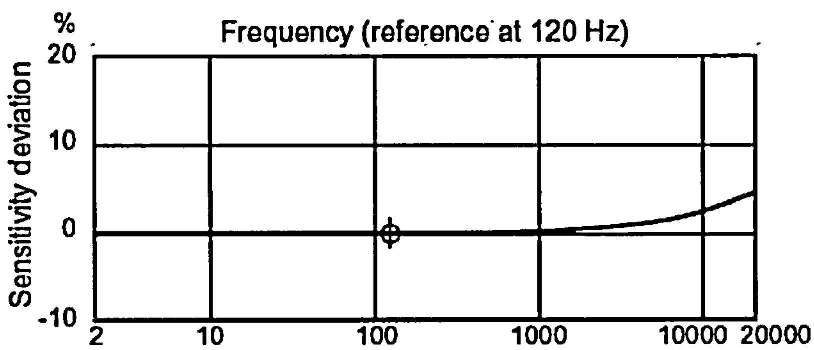


Figure 4: Sensitivity vs. Frequency - CP-211



The frequency range of interest for this test is 5 Hz to 400 Hz, and in this region the response is flat, so the variation in sensitivity with frequency is negligible.

f) Sensitivity to Acceleration

The pressure sensors have a slight sensitivity to acceleration of the substrate, which is a conservative error for the pressure measurement. For the CP-104, the specified sensitivity to acceleration is < 0.1 pC/g, while the measured sensitivity (based on calibration tests) is about 0.02 pC/g, a factor of 5 less. The maximum acceleration is expected to be < 5 g, so the maximum error is < 0.1 pC based on the measured acceleration sensitivity. This is a small fraction (< 0.5%) of the typical CP-104 pressure reading, and it is in the conservative direction. This is valid also for CP-211. So it is justified to neglect the error due to acceleration for pressure measurements.

g) Established Sensor Sensitivity

Based on the evaluation of the various factors that could affect sensor sensitivity (Section 4.1.2.1 items a through f) , the recommended sensitivity of the pressure sensors used for the QC2 test are as follows:

$S_{CP\text{-}104}$ = Sensitivity for QC2 CP-104 = Sensor dependent (Table 1 Column 4)

$S_{CP\text{-}211}$ = Sensitivity for QC2 CP-211 = Same for all sensors = 1.8 ± 2.6% pC/psi

The variability in sensitivity for the CP-211 sensors represents an uncertainty in the absolute value of pressure measured by them. But this uncertainty is due to an uncertainty in the knowledge of the initial sensitivity. Thus although the sensitivity for any CP-211 sensor is uncertain by 2.6%, this uncertainty does not apply when comparing measurements at different times from the same sensor. For such comparisons only the sensor sensitivity drift error (which is negligible for CP-211) and the sensor and electronic equipment random errors are applicable.

4.1.2.2. Dynamic Sensor Linearity Error

The specified linearity of all the pressure gauges is ± 1% (Ref. 5, 6). This is a percent of point error, so if the peak of the dynamic pressure fluctuations was 5 psi, the sensor linearity error would be 0.05 psi. For lower magnitude fluctuations, the error would be correspondingly smaller. Thus the random error due to sensor linearity is:

$dE_{Press.\ Sensor} = \pm 1\%$

4.1.3 Pressure Sensor Electronics

The specified random errors for the electronic components are as follows:

4.1.3.1. Charge Converter error

The charge converter has a stability specification of 0.03% per deg C (Ref. 11). The temperature variation under operating conditions at the location of this device is conservatively estimated to be ± 5 deg C. So the random error for the charge converter is:

Charge Converter error = ± 0.15 %.

4.1.3.2. Galvanic Separation Unit error

The Galvanic Separation Unit has a stability specification of 0.02% per deg C (Ref. 12). The temperature variation under operating conditions at the location of this device is conservatively estimated to be ± 5 deg C. So the random stability error is 0.10 %. In addition, this unit also has a linearity specification of 0.5% over the dynamic measuring range, so the combined random error of this device is:

GSI error = $\pm (0.10^2 + 0.5^2)^{1/2} = \pm 0.51$ % (conservative roundup)

4.1.3.3. Signal Processing Unit error

The Signal Processing Unit has an adjustment precision on conditioner input of ± 1% and adjustment precision on calibration input of ± 1.5% (Ref. 13). So the combined random error of this device is:

$$\text{Signal Processing error} = \pm (1.0^2 + 1.5^2)^{1/2} = \pm 1.8\ \%$$

4.1.3.4. Data Acquisition System error

The DAS with the analog front end amplifier has a specified gain error of 0.1% and an offset error of .075% of Full Scale on the high (10V) scale and 0.25% of Full Scale on the low (1V) scale (Ref. 14). The actual error measured by calibration is at least a factor of 5 lower (Ref. 14). So conservatively, for practical settings and readings the random error of this device can be taken to be:

$$\text{DAS error} = \pm (0.1^2 + 0.75^2 + 0.25^2)^{1/2} = \pm 0.3\ \%$$

The error introduced by the 24 bit A/D conversion is negligible.

4.1.3.5. Overall Electronics error

The overall random electronics error based on specified accuracies of the electronic devices is the SRSS of the errors in 4.1.3.1 through 4.1.3.4 The result is:

$$\text{Overall Specified Electronics Error} = (0.15^2 + 0.51^2 + 1.8^2 + 0.3^2)^{1/2} = \pm 1.9\%$$

This error does not include drift of electronic devices with time, because the vendor does not specify it. To account for time drift, a conservative assumption taken from NRC approved instrument setpoint methodology (Ref. 15) is to assume that the drift for 6 months (or less) is equal to the instrument accuracy. Thus over the test period of 6 months the overall electronics error, including accuracy and drift, is:

$$dE_{\text{Electronics}} = \text{Overall Electronics Error} = (1.9^2 + 1.9^2)^{1/2} = \pm 2.7\%$$

4.1.4 Overall Pressure Sensor Loop Error

For the CP-104 pressure measurements, the sensor sensitivity is known (4.1.2.1 item g), so the overall error in the pressure is the SRSS of the dynamic sensor linearity error from Section 4.1.2.2, and overall electronic error from 4.1.3.5. Thus:

$$\text{Overall Pressure Error}_{\text{CP-104}} = \pm (1.0^2 + 2.7^2)^{1/2} = \pm 2.9\ \%\ \text{(conservative roundup)}$$

For the CP-211 pressure measurements there is a ± 2.6% uncertainty in sensitivity that needs to be considered. So the uncertainty in absolute pressure is:

$$\text{Absolute Pressure Error}_{\text{CP-211}} = \pm (2.6^2 + 2.9^2)^{1/2} = \pm 3.9\ \%$$

For comparing results for any one CP-211 sensor, the error is the same as for CP-104:

$$\text{Relative Pressure Error}_{\text{CP-211}} = \pm 2.9\ \%$$

According to accepted methods (Ref. 15), the specified random errors are treated as 2σ errors. This implies that for CP-104, where each sensor sensitivity is known, there is

95% probability that the actual pressure is within ± 2.9 % of the measured value for each sensor. For CP-211 there is 95% probability that the absolute pressure is within ± 3.9 % of the measured value for each sensor, and that the relative pressures for any one sensor are within ± 2.9 %. There is some conservatism in these values because the sensor sensitivity has been established conservatively.

4.1.5 Impact of Pressure Sensor Cover Plate on Measured Pressure

Most pressure sensors (pressure sensor type CP-104) were installed on the dryer hood *surface directly in order to avoid drilling multiple holes on the hood surface and mounting* from behind. Hence the sensing diaphragm of the pressure transducers are not flush mounted with the surface of the hood. A stream lined sensor cover plate was designed for each of these sensors in order to minimize flow disturbances and thus affecting the pressure measurement. Analyses were performed and wind tunnel tests were conducted to study the effect of the cover plate on measured pressure. The details are of the analysis and tests as well as the results and recommendations are reported in Reference 4 of this report.

The results indicate that the measured pressure with sensor cover plates are 0 to 8% higher than if they were flush mounted, with the exception of four pressure sensors which are installed directly in front of each of the steam nozzles. This is conservative because the actual pressure is lower than the measured pressure by up to 8%. The correction factor, $F_{Coverplate}$ (multiplier for the measured pressure to get actual pressure) is frequency dependent and has a maximum value of 1 between the frequency band of 5 to 200 Hz. For conservatism, $F_{Coverplate}$ can be assumed as 1.

The four pressure sensors located directly in front of each of the steam nozzles, the correction factor has to be determined by further analysis. Additional details are discussed in Reference 4 of this report.

Table 1: Measured Sensitivities of QC2 CP-104 Pressure Sensors

Sensor	Measured Sensitivity	Deviation at 300 °C	Recommended Sensitivity
#	(pC/bar)	(%)	(pC/psi)
95846	211	1.9	14.5
95847	212	3.14	14.6
95848	211	2.46	14.5
95849	209	2.61	14.4
95850	210	2.12	14.5
95851	214	2.44	14.8
95852	213	1.98	14.7
95853	219	1.1	15.1
95854	212	2.1	14.6
95855	215	1.8	14.8
95856	217	1.6	15.0
95857	216	2.2	14.9
95858	218	1.8	15.0
95859	213	-0.6	14.6
96126	213	0.8	14.7
96127	212	0.6	14.6
96128	208	0.4	14.3
96129	211	-0.9	14.4
96130	210	0.1	14.5
96131	215	2.1	14.8
96132	214	1.6	14.8
96133	213	1.9	14.7
96134	212	0.5	14.6
96135	213	0.4	14.7
96136	210	-1.8	14.2

4.2 Acceleration Measurement Loop

4.2.1 Transfer Function

For this QC2 test, the acceleration measurement is a measurement of the dynamic acceleration as a function of time and frequency in the range of interest (~ 5 to 400 Hz). The piezoelectric acceleration sensor, which is specially designed for dynamic measurements, outputs a charge proportional to the acceleration of the substrate. The transfer function for the accelerometer is the same as for the pressure sensor (Section 4.1.1), and the output signal is directly proportional to the input acceleration. The transfer function and error equations shown in Section 4.1.1 for the pressure sensor are also valid for the accelerometer, except the sensor sensitivity refers to the sensitivity of the accelerometer . As for the case of the pressure sensor, once the accelerator sensitivity (S_A) is established, and the transfer function and gains of the electronic devices are known through calibration, the measured value (V) is related to the acceleration (A) as follows:

$$A = V / (K1 * K2 * K3 * K4 * S_A) \qquad (3)$$

Where

K1 = Charge Converter Unit Transfer Constant (milliamps / pC)

K2 = Galvanic Separator Unit Transfer Constant (Volts / milliamp)

K3 = Signal Processing Unit Transfer Constant (Output Volts / Input Volts)

K4 = DAS Transfer Constant (Digital Output Signal / DAS Input Voltage)

V = Value of Parameter read by DAS

S_A = Sensitivity of Pressure Sensor (pC / g)

The error in the measured acceleration (dA) due to linearity error of the sensor and the random errors of the electronic devices, is as follows:

$$dA = A \{1 \pm [\, dE_{Accelerometer}^2 + dE_{Electronics}^2 \,]^{1/2} \} \qquad (4)$$

Where

$dE_{Accelerometer}$ = Specified linearity error (%) of the accelerometer as a fraction

$dE_{Electronics}$ = Combined (SRSS) random error (%) of the electronic devices as a fraction

The accelerometer can be used to give the displacement. This is done by double integrating the signal (with respect to time) in sub-modules within the signal processing unit. For this measurement the signal processor outputs a voltage proportional to the double integral of the acceleration signal, and this is then amplified by the DAS amplifier. The transfer constants for the signal processing unit and the DAS amplifier could be different for the displacement measurement than the acceleration measurement. However, the transfer function for the displacement (X) is still linear, and can be written descriptively as follows:

$$X = V_{disp} / (S_A * K1 * K2 * K3_{disp} * K4_{disp}) \quad (5)$$

Where

V_{disp} = Displacement signal measured at DAS

$K3_{disp}$ = Signal Processing Unit Transfer Constant (Output Volts / double integral of the Input Volts)

$K4_{disp}$ = DAS Transfer Constant for Displacement signal (Digital Output Signal / DAS Input Voltage)

The error in the measured displacement is due to linearity error of the sensor and the random errors of the electronic devices (including the integration sub-modules), and can be written as follows:

$$dX = X \{1 \pm [dE_{Accelerometer}^2 + dE_{Electronics,\ Displacement}^2]^{1/2} \} \quad (6)$$

Where

$dE_{Accelerometer}$ = Specified linearity error (%) of the accelerometer as a fraction

$dE_{Electronics,\ Displacement}$ = Combined (SRSS) random error (%) of the electronic devices (including the error of the sub-modules used for integration) as a fraction

4.2.2 Accelerometer Sensors

This section establishes the accelerometer sensor sensitivity at operating conditions, and specifies the dynamic sensor linearity error.

4.2.2.1. Establish Sensor Sensitivity

a) Sensitivity at Calibration Temperature (Room Temp)

The accelerometer sensors output a charge (picocoulombs) per g of acceleration, and for the CA-901 sensor used in the QC2 instrumentation, the following nominal sensitivity is applicable at room temperature (23 deg C)

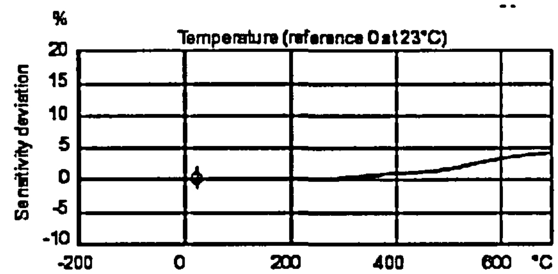
CA-901 Sensitivity (Specified) = 10 pC/g ± 5% (Ref. 16)

Each CA-901 sensor to be used in the QC2 test was calibrated separately (Ref. 17), and the calibrated sensitivities are shown in Table 2. It is recommended that these measured sensitivities be used as the CA-901 sensor room temperature sensitivities for QC2 data analysis. Using the calibrated sensitivities will obviate the need for considering the 5% tolerance in sensitivity due to manufacturing tolerances.

b) Sensitivity at Operating Temperature

The sensitivity of the CA-901 sensors increases with temperature, as shown in Figure 5

Figure 5: Sensitivity vs. Temperature - CA-901



From this figure there is no significant increase in sensitivity between room conditions and the operating conditions (~288 deg C). Thus although the measured data on the sensors show a slight increase ~ 1.5% at 300 deg C, it is recommended that the measured room temperature values be used since it is conservative. So for QC2 CA-901 sensors it is recommended that the following values be used:

Sensitivity for QC2 CA-901 = See Table 2 Column 4

(No additional temperature correction required)

These sensitivity values have a justifiable basis and are considered to be conservative.

c) Radiation Effect

The piezoelectric accelerometers have the same materials as the piezoelectric pressure sensors. So as described in Section 4.1.2.1 item c, the effect of radiation on the accelerometer sensor sensitivity can be assumed to be negligible.

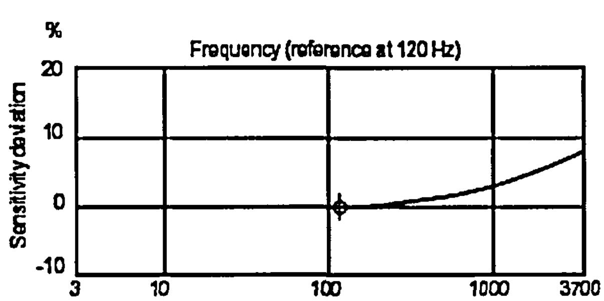
d) Sensor Sensitivity Drift with Time

Based on the material properties and description given in Section 4.1.2.1 item d, the accelerometer sensor sensitivity drift with time can be assumed to be negligible.

e) Sensor Sensitivity variation with frequency

The frequency response for the CA-901 accelerometers from the vendor data sheets (Ref. 16) is shown in Figure 6.

Figure 6: Sensitivity vs. Frequency - CA-901



This data shows that there could be a 2% increase in sensitivity at 400 Hz. However the measured data (Ref. 17) show that the increase is negligible. Thus since maintaining a lower sensitivity is conservative, it is justified to neglect the variation in sensitivity with frequency.

f) Sensitivity to Transverse Acceleration

The accelerometers have a slight sensitivity to transverse acceleration of the substrate, which is a conservative error since it results in an overestimation of the longitudinal compression mode acceleration measured by the CA-901 accelerometer. For the CA-901, the specified transverse sensitivity is < 5% (Ref. 16), while the measured sensitivity (based on calibration tests, Ref. 17) is approximately a factor of 5 less. The maximum transverse acceleration is expected to be less than that the longitudinal acceleration, so the maximum error is small. In addition the error is in the conservative direction. So it is justified to neglect the error due to transverse acceleration in the accelerometer measurements.

g) Established Sensor Sensitivity

Based on the evaluation of the various factors that could affect sensor sensitivity (Section 4.2.2.1 items a through f), the recommended sensitivity of the accelerometers used for the QC2 test is as follows:

$S_{CA\text{-}901}$ = Sensitivity for QC2 CA-901 = Sensor dependent (Table 2 Column 4)

4.2.2.2. Dynamic Sensor Linearity Error

The specified linearity of the accelerometer is ± 1% over the dynamic measuring range (Ref. 16). This is a percent of point error, so if the peak of the dynamic acceleration fluctuation was 2 g, the sensor linearity error would be 0.02 g. For lower magnitude fluctuations, the error would be correspondingly smaller.

4.2.3 Accelerometer Sensor Electronics

The specified linearity errors for the electronic components are the same as described for the pressure sensor electronics in Section 4.1.3. Thus, as shown in Section 4.1.3.5, the overall random electronics error for the acceleration measurement is:

Overall Electronics Error (acceleration measurement) = ± 2.7%

For the displacement measurement, the signal conditioner error is slightly greater than for the acceleration measurement. This increase has not been specified in the Vibro-Meter Signal Conditioner Module, however, based on similar vibration electronics (Ref. 18), the increase in error is approximately 1%. So the accuracy of the signal conditioner electronics increases from 1.8% to 2.8%, and the overall specified electronics error becomes:

Overall Displacement Electronics Error = $(0.15^2 + 0.55^2 + 2.8^2 + 0.3^2)^{1/2} = \pm 2.9\%$

Assuming again that the drift error for 6 months is equal to the specified accuracy, the overall electronics error becomes:

Overall Displacement Electronics Error (including drift) = $(2.9^2 + 2.9^2)^{1/2} = \pm 4.1\%$

4.2.4 Overall Accelerometer Loop Error

Using the established sensor sensitivity shown in 4.2.2.1 item g, the overall random error in the pressure is the SRSS of the dynamic sensor linearity error from Section 4.2.2.2 and overall electronic error from 4.2.3. Thus:

Overall Acceleration $\text{Error}_{CA\text{-}901} = \pm (1.0^2 + 2.7^2)^{1/2} = \pm 2.9$ % (conservative roundup)

For the displacement measurement, the overall loop error is:

Overall Displacement $\text{Error}_{CA\text{-}901} = \pm (1.0^2 + 4.1^2)^{1/2} = \pm 4.2$ % (conservative roundup)

According to accepted methods (Ref. 14), the specified random errors are treated as 2σ errors. This implies that assuming the sensor sensitivity is correct, there is 95% probability that the actual acceleration is within ± 2.9 % of the measured value and the actual displacement value is within ± 4.2 % of the measured value. However, there is some conservatism in the acceleration and displacement measurements because the sensor sensitivity has been established conservatively.

Table 2: Measured Sensitivities of QC2 CA-901 Accelerometers

Sensor	Measured Sensitivity	Deviation at 300 °C	Recommended Sensitivity
#	(pC/g)	(%)	(pC/g)
95860	9.90	1.60	9.90
95861	10.05	0.65	10.05
95862	10.02	1.50	10.02
95863	9.98	2.00	9.98
95864	9.92	1.50	9.92
95865	10.10	1.50	10.10
95866	9.96	1.75	9.96
95867	10.00	2.10	10.00
95868	9.92	1.85	9.92

4.3 Strain Gauge Measurement Loop

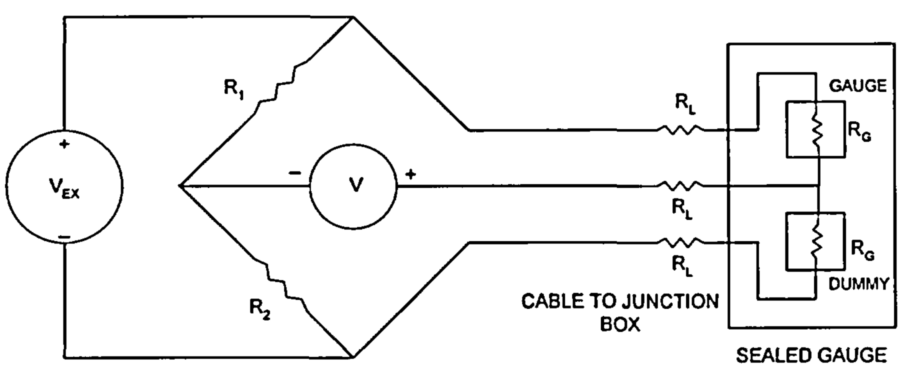
4.3.1 Transfer Function

For this QC2 test, there are two strain measurements, one on the dryer and the other on the main steam lines, and two types of strain gauges (but with the same interfacing electronics) are used for these measurements. The strain measurement is a measurement of the dynamic strain as a function of time and frequency in the range of interest (~ 5 to 400 Hz). The strain gauge sensor, which is specially designed for dynamic measurements, outputs a voltage proportional to the strain (dL/L) induced on the substrate onto which it is welded. Since this measurement is only concerned with dynamic changes, a reference to strain in this section is a reference to the dynamic strain which is the change over the static strain. The strain changes the resistance of the gauge and produces a voltage in the Wheatstone bridge measurement circuit which is approximately linearly proportional to the strain.

1) Dryer Strain Gauge

The strain gauge used for the dryer strain measurements is a Wheatstone bridge with a strain gauge resistor as one arm, a dummy resistor (same resistance as the strain gauge) as another arm, and two precision balanced resistors (R_1 and R_2) for the other two arms. The circuit, called a half bridge circuit (or sometimes called a quarter bridge II circuit) is shown in Figure 7.

Figure 7: Dryer Strain Gauge Configuration



The transfer function for the dynamic strain measurement for this circuit can be derived from the general equation for an unbalanced Wheatstone bridge. Assuming no change in temperature while the dynamic measurement is made, the change in strain due to temperature can be neglected, and the dynamic strain would be given by:

$$\varepsilon = \frac{-4V_r}{GF(1+2V_r)}\left(1+\frac{R_L}{R_G}\right) \quad (7)$$

Where:

ε = Dynamic Strain (microstrain)

V_r = Dynamic Signal voltage as fraction of excitation voltage = V / V_{Ex}

V = Dynamic Signal voltage from dynamic strain

V_{Ex} = Excitation Voltage

GF = Gauge Factor due only to strain on gauge at operating temp = $\dfrac{dR_G / R_G}{dL / L}$

R_L = Lead Resistance at operating temperature (measured by calibration)

R_G = Gauge Resistance at operating temperature (measured by calibration)

The presence of the $1+2V_r$ term in the denominator introduces a slight non-linearity in the transfer function. However, since $2V_r$ is significantly less than 1, the non-linearity is not significant. However, it can be accounted for if necessary.

The dynamic strain amplifier and DAS system amplify the signal voltage linearly. So, with the assumption that the non-linearity can be neglected, the overall transfer function between the measured voltage and strain is:

$$\varepsilon = V / (K5 * K6 * S_{Dryer\ Strain\ Gauge}) \qquad (8)$$

Where,

V = Measured strain value at the DAS (DAS voltage/input volt)

K5 = Dynamic Strain Amplifier Gain (Volts/microVolt)

K6 = DAS Transfer Constant (Digital Output Signal / DAS Input Voltage)

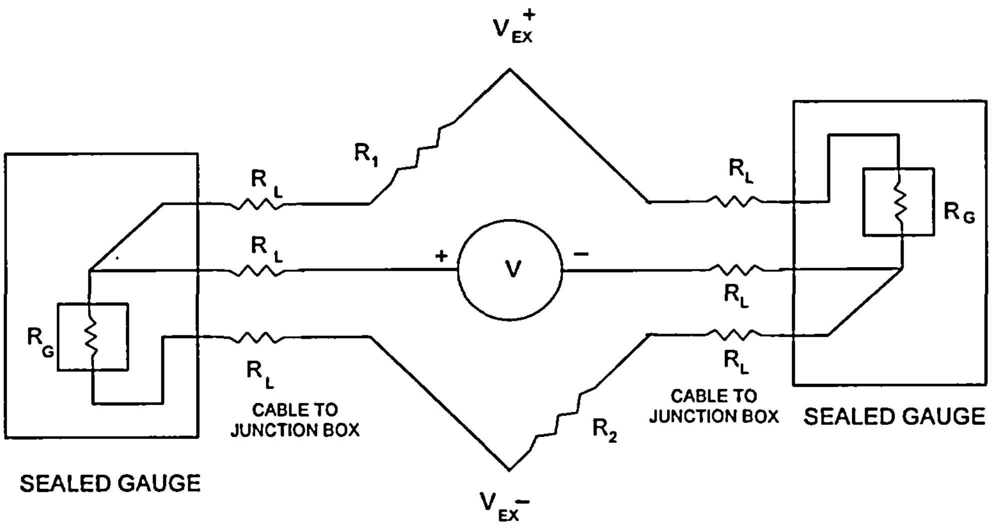
$S_{Dryer\ Strain\ Gauge}$ = Dryer Strain Gauge Sensitivity

$$= V_{Ex} / \{ \frac{-4}{GF_{Dryer Strain\ Gauge}} \left(1 + \frac{R_L}{R_G}\right) \} \text{ microVolt / microstrain}$$

2) MSL Strain Gauge

The strain gauge used for the MSL strain measurements is the same Wheatstone bridge circuit, however there is no dummy resistor in the sealed gauge sensor element. This a half bridge circuit with two strain gages combined to form the opposite arms of the Wheatstone bridge to improve the sensitivity. This configuration is shown in Figure 8.

Figure 8: MSL Strain Gauge Configuration



Assuming no change in temperature while the dynamic measurement is made, the change in strain due to temperature can be neglected, and the dynamic strain would be given by:

$$\varepsilon = \frac{2V_r}{GF_{MSL}(1-V_r)}\left(1+\frac{R_L}{R_G}\right) \qquad (7)$$

Where:

- ε = Dynamic Strain (microstrain)
- V_r = Dynamic Signal voltage as fraction of excitation voltage = V / V_{Ex}
- V = Dynamic Signal voltage from dynamic strain
- V_{Ex} = Excitation Voltage
- GF_{MSL} = Gauge Factor due only to strain on gauge at operating temp = $\frac{dR_G / R_G}{dL/L}$
- R_L = Lead Resistance at operating temperature (measured by calibration)
- R_G = Gauge Resistance at operating temperature (measured by calibration)

The presence of the $(1 - V_r)$ term in the denominator introduces a slight non-linearity in the transfer function. However, since V_r is significantly less than 1, the non-linearity is not significant. However, it can be accounted for if necessary.

The transfer function is

$$\varepsilon = V / (K7 * K8 * S_{MSL\ Strain\ Gauge}) \qquad (9)$$

Where,

V = Measured strain value at the DAS (DAS voltage/input volt)

K7 = Dynamic Strain Amplifier Gain (Volts/microVolt)

K8 = DAS Transfer Constant (Digital Output Signal / DAS Input Voltage)

$S_{MSL\ Strain\ Gauge}$ = MSL Strain Gauge Sensitivity

$$= V_{Ex} / \left\{ \frac{2}{GF_{MSL\ Strain\ Gauge}} \left(1 + \frac{R_L}{R_G}\right) \right\} \text{ microVolt / microstrain}$$

For each strain gauge measurement loop, the error in the measured strain ($d\varepsilon$) due to linearity error of the strain gauges and the random errors of the electronic devices, is as follows:

$$d\varepsilon = \varepsilon \{1 \pm [\, dE_{Strain\ Gauge}^2 + dE_{Electronics}^2 \,]^{1/2} \} \qquad (10)$$

Where

$dE_{Strain\ Gauge}$ = Specified linearity error (%) of the strain gauge sensor as a fraction

$dE_{Electronics}$ = Combined (SRSS) random error (%) of the electronic devices as a fraction

4.3.2 Strain Gauge Sensors

This section establishes the strain gauge sensor sensitivity at operating conditions, and specifies the dynamic sensor linearity error.

<u>4.3.2.1. Establish Sensor Sensitivity</u>

a) <u>Sensitivity at Calibration Temperature (Room Temp)</u>

The strain gauge sensors output a microvolt output per microstrain of the substrate to which they are welded. For the sensors used in the QC2 instrumentation, the following nominal Gauge Factors (proportional to sensitivity) are applicable at room temperature (23 deg C)

1) Kyowa KHC-10 Strain Gauges on dryer (nominal) GF = 1.65 (Ref. 19)
2) Hitec HBWAK-35 Strain Gauges on MSL (nominal) GF = 2.1 (Ref. 20)

These gauge factors represent "natural" gauge factors referring only to the change in resistance of the gauge element, and do not include the effects of the cables. Thus they are the gauge factors needed for strain calculation using equation 7, 8 and 9. Each Kyowa strain gauge was calibrated separately (Ref. 21). However the calibrated gauge factors included the effect of the cables and so they are not appropriate for use in the dynamic strain measurements discussed in equation 7, 8 and 9. It is more correct to assume that all Kyowa strain gauges have a natural GF of 1.65 at room temperature, and that the variability due to manufacturing tolerances is as derived from the calibration measurements. A review of the calibration data for the QC2 Kyowa strain gauges shows that the 2-sigma variation in sensitivities was ≤ 4% due to manufacturing tolerances. Thus the GF at room temperature is:

GF (Kyowa KHC-10 Strain Gauges on dryer) = 1.65 ± 4% (Room Temp)

Individual calibration data is not available for the Hitec gauges, so for these the nominal value, reduced by the specified variability in the gauge factor is conservatively recommended. The specified variability is ± 2% (Ref. 21). Thus the GF at room temperature, is:

GF (Hitec HBWAK-35 Strain Gauges on MSL) = 2.1 ± 2% (Room Temp)

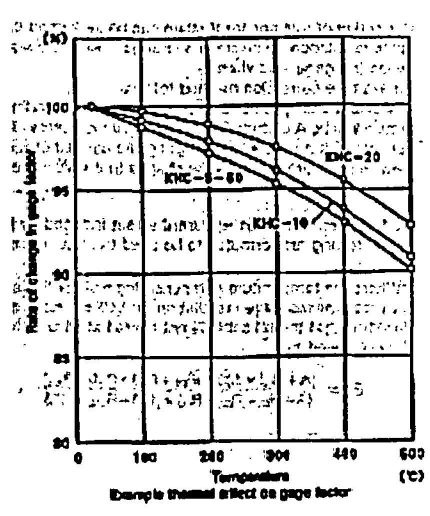
b) Gauge Factor at Operating Temperature

The gauge factor of these sensors decreases with temperature. It is necessary to correct for this decrease because as shown in equations 8 and 9, not correcting would mean a lower calculated strain and that is non-conservative.

For the Kyowa strain gauge the temperature variation is shown in Figure 9 (Ref. 23). From this data the GF reduction for the operating temperature of 550 deg F is conservatively estimated to be 4%. Thus the applicable GF for evaluation of the QC2 dryer strain using Kyowa strain gauges is:

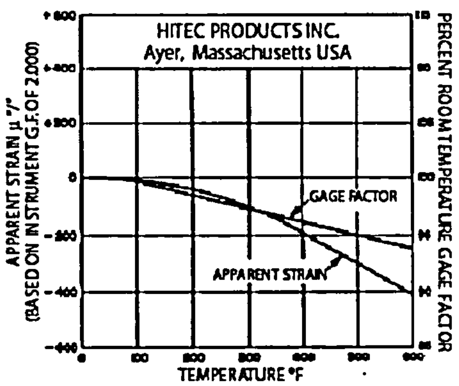
GF (Kyowa KHC-10 Strain Gauges on dryer) = 1.58 ± 4% (Operating Temp)

Figure 9: GF vs. Temperature - Kyowa KHC-10 Strain Gauge



For the Hitec strain gauge the temperature variation is shown in Figure 10 (Ref. 24).

Figure 10: GF vs. Temperature - Hitec HBWAK-35 Strain Gauge



From this data the GF reduction for the operating temperature of 550 deg F is conservatively estimated to be 6%. Thus the applicable GF for evaluation of the QC2 MSL strain using Hitec strain gauges is the room temperature value less 6%:

GF (Hitec HBWAK-35 Strain Gauges on dryer) = 1.97 ± 2% (Operating Temp)

These gauge factor values have a justifiable basis and are considered to be conservative.

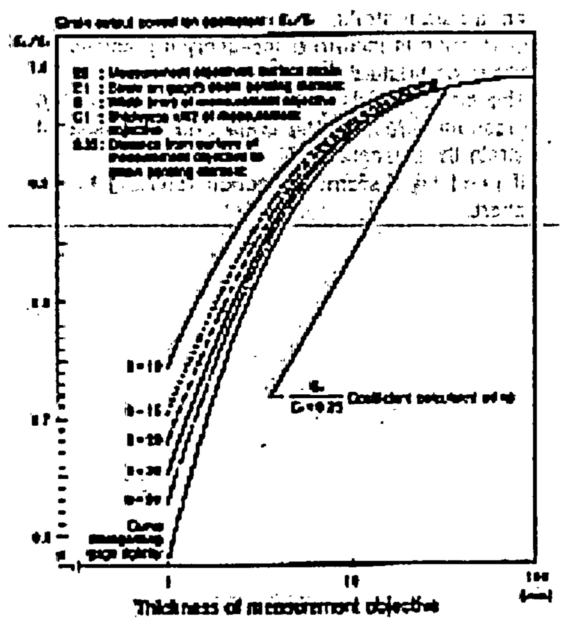
c) Thickness and Rigidity Effect

When the strain gauge is mounted on the substrate there generally is a separation between the sensing element and the substrate due to the weld material. This affects the measurement of bending strain in a manner to produce a measurement value larger than the true value. The thinner the substrate on which the gauge is mounted, the more the measurement is affected. Since this effect measures a strain that is larger than the true strain, it is conservative. However, for accurate measurements it should be considered.

For the Kyowa strain gauges the separation distance between the sensing element and the substrate is specified to be 0.35 mm and the impact on the dryer strain measurement can be evaluated from the data shown in Figure 11 taken from the Kyowa manual (Ref. 23). This data shows that the correction factor depends upon the thickness of the dryer substrate that is being measured (C = half thickness), and the rigidity of the substrate. Using the most conservative curve where the rigidity of the substrate is disregarded, the correction factor varies from 0.82 to 0.95 for 1/8 inch to 1/2 inch thick dryer substrate and has a value of approximately 0.9 for a typical dryer material thickness of 1/4 inch.

Note that a different sensitivity correction factor is applicable to strain gauges mounted on dryer locations which have different dryer thicknesses.

Figure 11: Thickness Correction Factor - Kyowa KHC-10 Strain Gauge



For the Hitec strain gauges no data is available. However the correction factor is small because the separation distance for the Hitec foil-based gauge design is less than that for the Kyowa wire-based design, and the thickness of the MSL pipe wall is large (~ 1 inch) compared to the dryer material thickness. With the conservative assumption that the separation distance for the Hitec gauge is the same as for the Kyowa gauge, but using the substrate thickness of 1 inch, the correction factor is 0.97. This is a conservative factor for the Hitec strain gauge.

d) Radiation Effect

These strain gauges are made from radiation resistant materials, and have been used in nuclear radiation environments. However, there is no published data on radiation sensitivity of these strain gauges. Based on an evaluation of the gauge and cable construction materials, it is expected that for the 6 months duration of the test the effect of the radiation insignificant and within the conservatisms used to establish the Gauge Factor.

e) Sensor Sensitivity Drift with Time

The Kyowa strain gauge vendor specifies a drift of 20 microstrains per hour for a 6 hour test at 500 deg C. However this is believed to be a change in thermally induced apparent strain, and not a drift that would cause an error in the dynamic measurement.

The Hitec vendor does not specify drift with time, and has stated (Ref. 10) that as long as the temperature does not drift with time, the Gauge Factor will also not drift with time. Thus for each strain gauge the Gauge Factor for dynamic measurement can be assumed constant for the duration of the test.

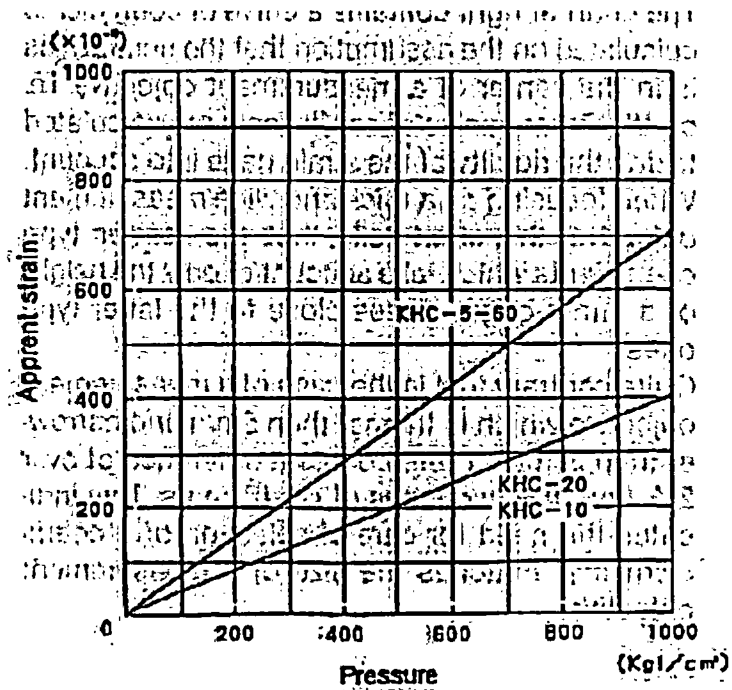
f) Sensor Sensitivity variation with frequency

Since the strain gauge is primarily a resistor, the frequency response is determined primarily by the cable, and is flat well into the Kilo Hertz region (5 KHz for Kyowa, Ref. 19). Thus the GF can be assumed to be the same at all frequencies in the region of interest (5 to 400 Hz).

g) Sensitivity to Pressure

Pressure on the encapsulated strain gauge can generate apparent strain, and this could be a potential source of error for static dryer strain measurements since those strain gauges are at ~ 1000 psi under operating conditions. There is no concern for the MSL strain gauges because they are mounted on the outside of the MSL pipes at atmospheric pressure. For the Kyowa KHC-10 series strain gauges mounted on the dryer inside the reactor, the 1000 psi (~ 70 Kgf/cm^2) operating pressure can induce an apparent strain of approximately 28 microstrains as shown in Figure 12 taken from the vendor literature (Ref. 23). This apparent strain caused by the static pressure is like an additional thermally induced apparent strain, and these can be neglected for dynamic strain measurements. Dynamic changes in pressure can affect the dynamic strain measurement, but since the dynamic pressure changes are small (< 7 psi), the effect is negligible (< 0.2 microstrain) in comparison with the actual dynamic strain values (< 100 microstrains). In addition the error is in the conservative direction because it tends to increase the measured strain. Thus it is justifiable to neglect this error for the strain measurements.

Figure 12: Pressure Induced Apparent Strain - Kyowa KHC-10 Strain Gauge



Pressure-induced apparent strain

h) Established Sensor Sensitivity

Based on the evaluation of the various factors that could affect strain gauge sensitivity (Section 4.3.2.1 items a through g) , the recommended sensitivity of the strain gauge sensors used for the QC2 test after reducing for the temperature and thickness factor, are as follows:

$GF_{\text{Kyowa Strain Gauge}}$ (1/8 inch dryer thickness) = 1.29 ± 4%

$GF_{\text{Kyowa Strain Gauge}}$ (1/4 inch dryer thickness) = 1.42 ± 4%

$GF_{\text{Kyowa Strain Gauge}}$ (1/2 inch dryer thickness) = 1.50 ± 4%

$GF_{\text{Hitec Strain Gauge}}$ (1 inch MSL wall thickness) = 1.91 ± 2%

These values have been obtained by conservatively rounding down.

4.3.2.2. Dynamic Sensor Linearity Error

As discussed in Section 4.3.1, the linearity of strain gauges has a slightly non-linear response. The error is systematic and not random, but is not significant and can be ignored.

$dE_{\text{Strain Gauge}}$ = negligible

4.3.3 Strain Gauge Electronics

The specified linearity errors for the electronic components are as follows:

4.3.3.1. Dynamic Amplifier and Signal Conditioner

The dynamic amplifier has a stability specification of 0.05% per deg C (Ref. 25). The temperature variation under operating conditions at the location of this device is conservatively estimated to be ± 5 deg C. So the random temperature error for the amplifier is ± 0.25%. In addition there is a specified non-linearity error of ± 0.2%, and a sensitivity adjuster step accuracy of ± 0.5%. The overall amplifier random error is:

Dynamic Amplifier error = $\pm (0.25^2 + 0.2^2 + 0.5^2)^{1/2}$ = 0.60% (conservative roundup).

There is also a scale factor that must be considered. This scale factor is due to the fact that the amplifier gain (or transfer function) stated on the instrument is based on the assumption that GF = 2. So for an actual gauge factor = GF, the scale correction is 2/GF (Ref. 23). This is not an error, and merely has to be accounted for in the value of amplifier gain or transfer function.

The accompanying signal conditioner has a stability specification of 0.02% per deg C (Ref. 25). For a ± 5 deg C temperature variation the random temperature error for the signal conditioner is ± 0.10%. In addition there is a specified non-linearity error of ± 0.05%, and a sensitivity adjuster step accuracy of ± 0.2%. The overall signal conditioner random error is:

Signal Conditioner error = $\pm (0.10^2 + 0.05^2 + 0.2^2)^{1/2}$ = 0.23% (conservative roundup).

Thus the overall amplifier and signal conditioner random error is:

Dyn Amp & Signal Cond error = $\pm (0.60^2 + 0.23^2)^{1/2}$ = 0.65% (conservative roundup).

4.3.3.2. Data Acquisition System error

The DAS used for the strain gauges and the pressure transducers is the same. Thus as shown in Section 4.1.3.4 the DAS random error is:

DAS error = ± 0.3 %

4.3.3.3. Overall Electronics error

The overall random electronics error based on specified accuracies of the electronic devices is the SRSS of the errors in 4.3.3.1 through 4.3.3.2. The result is:

Overall Specified Electronics Error = $(0.65^2 + 0.3^2)^{1/2} = \pm 0.72\%$

This error does not include drift of electronic devices with time, because the vendor does not specify it. To account for time drift, a conservative assumption taken from NRC approved instrument setpoint methodology (Ref. 15) is to assume that the drift for 6 months (or less) is equal to the instrument accuracy. Thus over a the test period of 6 months the overall electronics error, including accuracy and drift, is:

$dE_{Electronics}$ = Overall Electronics Error = $(0.72^2 + 0.72^2)^{1/2} = \pm 1.1\%$

This overall strain gauge electronics error value was calculated using conservative roundup.

4.3.4 Overall Strain Gauge Loop Error

For the dynamic strain measurements, the sensor sensitivity (Gauge Factor) is known to be within ± 4% for the Kyowa strain gauges and ± 2% for the Hitec strain gauges, as described in Section 4.3 2.1 h. So the accuracy of the absolute strain measurement is the SRSS of the sensor sensitivity uncertainty and the overall electronics error in Section 4.3.3.3. Thus the uncertainty in absolute strain is:

$$\text{Absolute Strain Error}_{Kyowa} = \pm\,(4.0^2 + 1.1^2) = 4.2\ \%\ \text{(conservative roundup)}$$

$$\text{Absolute Strain Error}_{Hitec} = \pm\,(2.0^2 + 1.1^2) = 2.3\ \%\ \text{(conservative roundup)}$$

For comparing results for any one strain gauge, the relative error is just the electronics error. Thus the relative strain error is:

$$\text{Relative Strain Error}_{Kyowa\ and\ Hitec} = \pm\ 1.1\ \%$$

According to accepted methods (Ref. 15), the specified random errors are treated as 2σ errors. This implies that there is 95% probability that on an absolute scale the measured strain is accurate to within ± 4.2 % for Kyowa and ± 2.3 % for the Hitec measurements. On a relative scale, for each strain gauge, there is 95% probability that the measured strain is accurate to within ± 1.1 % for both Kyowa and Hitec measurements.

5. Summary & Conclusions

1) The accuracy of the dynamic measurements of Pressure, Acceleration, Displacement, and Strain has been calculated using the principles given in ISA-S67.04.
2) The detector sensitivity values for each CP-104 pressure sensor at operating conditions, based on conservative extrapolation of actual room temperature calibration data, are shown in Section 4.1.2.1g. Neglecting this conservatism, the error in the pressure measurement from these sensors, due to sensor non-linearity and random error of the interfacing electronics, and was calculated (Section 4.1.4) to be ± 2.9%. Cover plate correction is frequency dependent and conservatively used as 1. Cover plate correction factor for CP-104 in front of steam nozzles requires further analysis.
3) Calibration data was not available for the CP-211 pressure sensors. The detector sensitivity at operating conditions for these sensors was determined (Section 4.1.2.1g) to be 1.8 ± 2.6% pC/psi. These values were based on the specified CP-211 sensitivity, and it was assumed that the variability (due to manufacturing tolerances) was the same as for the CP-104 pressure sensors. On an absolute scale the measured pressure by these sensors is accurate to within ± 3.9 %, and on

a relative scale (i.e. for comparing pressure measurements from the same sensor at different times) the error was ± 2.9 % (Section 4.1.4).

4) The absolute pressure measurement errors discussed in this report neglect the effect of the dome built on some pressure sensors to facilitate installation. This effect is being studied in the wind tunnel tests, and will be reported on later.

5) The detector sensitivity values for each CA-901 acceleration sensor at operating conditions based on conservative extrapolation of actual room temperature calibration data, are shown in Section 4.2.2.1g. Neglecting this conservatism, the error in the acceleration and displacement measurement from these sensors, due to sensor non-linearity and random error of the interfacing electronics, was calculated (Section 4.2.4) to be ± 2.9% for the acceleration measurement, and ± 4.2% for the displacement measurement.

6) Pertinent calibration data was not available for the strain gauges. The gauge factor at operating conditions for these gauges was determined (Section 4.3.2.1h) to be a function of the thickness of substrate on which it is mounted. The values were determined to be:

   $GF_{\text{Kyowa Strain Gauge}}$ (1/8 inch dryer thickness) = 1.29 ± 4%

   $GF_{\text{Kyowa Strain Gauge}}$ (1/4 inch dryer thickness) = 1.42 ± 4%

   $GF_{\text{Kyowa Strain Gauge}}$ (1/2 inch dryer thickness) = 1.50 ± 4%

   $GF_{\text{Hitec Strain Gauge}}$ (1 inch MSL wall thickness) = 1.91 ± 2%

   These values were based on the specified gauge factors. The variability (due to manufacturing tolerances) for the Kyowa strain gauge was based on available calibration data, and for the Hitec strain gauge on vendor specifications. On an absolute scale the measured strain by these sensors is accurate to within ± 4.2 % for the Kyowa gauges and ± 2.3 % for the Hitec gauges. On a relative scale (i.e. for comparing strain measurements from the same gauge at different times) the error was ± 1.1 % (Section 4.3.4).

7) The calculated accuracies in this report apply individually to each sensor loop, and are based only on the sensor and electronic errors. Modeling errors which use the sensor readings to obtain the overall pressure loading on the dryer, are not included.

6. References

1. Steam Dryer Instrumentation Philosophy GE-NE-0000-0030-1244-01
2. Dryer Vibration Instrumentation - Design Specification, V. Ramani, 26A6395, June 2003
3. Setpoints for Nuclear Safety Related Instrumentation, ISA-S67.04 Part I, September 1994; Methodologies for Determination of Setpoints for Nuclear Safety Related Instrumentation, ISA-S67.04 Part II; September 1994
4. Summary of the Effects of the Sensor Cover Plates on Dynamic Pressure Measurements, GENE 0000-0038-2076-01
5. GE Reuter-Stokes Drawing E8-1000-202-2; Vendor (Vibro-Meter) Data Sheet for CP-104
6. GE Reuter-Stokes Drawing E8-1000-202-4X; Vendor (Vibro-Meter) Data Sheet for CP-211
7. Vibro-Meter Pressure Sensor Acceptance Test report Receipt # R04443A014, 10/27/2004; and Receipt # R04434B017, 10/21/2004
8. E-mail R. Blaser (Vibro-Meter) to Y. Dayal (GE), Re: Vibro-meter sensor radiation tolerance, 2/14/05
9. "Dresden and Quad Cities Top Guide Fluence Evaluation", S. Sitaraman, GENE 0000-0020-0971-R0, September 2003.
10. E-mail R. Blaser (Vibro-Meter) to Y. Dayal (GE), Re: Vibro-meter sensor drift, 2/15/05
11. Vibro-Meter IPC-629 Charge Converter Instruction Manual, 278-001/E, February 1985
12. Vibro-Meter GSI-130 Galvanic Separation Unit Instruction Manual, MAGSI 12230/E
13. Vibro-Meter UVC-629 Signal Processor Instruction Manual, 279-002/E, January 1985
14. LMS Instruments Certificate of Calibration SCADAS III, Report Number 141085C, 30 November 2004
15. GE Instrument Setpoint Methodology, NEDC-31336P-A, September 1996; based on the requirements in ISA-S67.04 (Reference 3).
16. GE Reuter-Stokes Drawing E8-1000-201-18;Vendor (Vibro-Meter) Data Sheet for CA-901
17. Vibro-Meter Accelerometer Sensor Acceptance Test report Receipt # R04434B016, 10/21/2004
18. Endevco Model 6634C Vibration Amplifier Specifications
19. GE Reuter-Stokes Drawing E8-1000-208-1; Data Sheet for Kyowa Strain Gauge Model Number KHC 10-120-G9
20. Data Sheet for Hitec Strain Gauge Model Number HBWAK-35-250-6-50FG-F
21. Kyowa Instruments Calibration Sheets for B487 - B503, Oct 1, 2004
22. E-mail S. Wnuk, Y. Hemingway (Hitec) to Y. Dayal, "Product Specifications for Hitec Strain Gauges" 2/17/05

23. Kyowa KHC Series Strain Gauge Instruction Manual, IM-G-010 '90.5, Soltec Corporation

24. Hitec Products Data Sheet "Weldable High Temperature Strain Gauges for 300 Deg C Static Measurements and 800 Deg C Vibratory Measurements"

25. Specifications for The DPM-71A Dynamic Strain amplifier and CD-71 Signal Conditioner,in Kyowa Multi-Conditioner MCD-16A Instruction Manual, IM-A-503b'01.10

ENCLOSURE 2

Additional Information Related to EPU Operation at Dresden and Quad Cities Nuclear Power Stations

ENCLOSURE 2

ATTACHMENT 1

Affidavit and "Quad Cities Replacement Steam Dryer Damping Values for Hood and Skirt Flow Induced Dynamic Analysis," GE-NE-0000-0032-1827-01P, GE Proprietary, dated April 2005

General Electric Company

AFFIDAVIT

I, **George B. Stramback**, state as follows:

(1) I am Manager, Regulatory Services, General Electric Company ("GE") and have been delegated the function of reviewing the information described in paragraph (2) which is sought to be withheld, and have been authorized to apply for its withholding.

(2) The information sought to be withheld is contained in GE proprietary report GE-NE-0000-0032-1827-01P, *Quad Cities Replacement Steam Dryer Damping Values for Hood and Skirt Flow Induced Dynamic Analysis*, Class III (GE Proprietary Information), dated April 2005. The proprietary information is delineated by a double underline inside double square brackets. Figures and large equation objects are identified with double square brackets before and after the object. In each case, the superscript notation[3] refers to Paragraph (3) of this affidavit, which provides the basis for the proprietary determination.

(3) In making this application for withholding of proprietary information of which it is the owner, GE relies upon the exemption from disclosure set forth in the Freedom of Information Act ("FOIA"), 5 USC Sec. 552(b)(4), and the Trade Secrets Act, 18 USC Sec. 1905, and NRC regulations 10 CFR 9.17(a)(4), and 2.390(a)(4) for "trade secrets" (Exemption 4). The material for which exemption from disclosure is here sought also qualify under the narrower definition of "trade secret", within the meanings assigned to those terms for purposes of FOIA Exemption 4 in, respectively, Critical Mass Energy Project v. Nuclear Regulatory Commission, 975F2d871 (DC Cir. 1992), and Public Citizen Health Research Group v. FDA, 704F2d1280 (DC Cir. 1983).

(4) Some examples of categories of information which fit into the definition of proprietary information are:

a. Information that discloses a process, method, or apparatus, including supporting data and analyses, where prevention of its use by General Electric's competitors without license from General Electric constitutes a competitive economic advantage over other companies;

b. Information which, if used by a competitor, would reduce his expenditure of resources or improve his competitive position in the design, manufacture, shipment, installation, assurance of quality, or licensing of a similar product;

c. Information which reveals aspects of past, present, or future General Electric customer-funded development plans and programs, resulting in potential products to General Electric;

d. Information which discloses patentable subject matter for which it may be desirable to obtain patent protection.

The information sought to be withheld is considered to be proprietary for the reasons set forth in paragraphs (4)a., and (4)b, above.

(5) To address 10 CFR 2.390 (b) (4), the information sought to be withheld is being submitted to NRC in confidence. The information is of a sort customarily held in confidence by GE, and is in fact so held. The information sought to be withheld has, to the best of my knowledge and belief, consistently been held in confidence by GE, no public disclosure has been made, and it is not available in public sources. All disclosures to third parties including any required transmittals to NRC, have been made, or must be made, pursuant to regulatory provisions or proprietary agreements which provide for maintenance of the information in confidence. Its initial designation as proprietary information, and the subsequent steps taken to prevent its unauthorized disclosure, are as set forth in paragraphs (6) and (7) following.

(6) Initial approval of proprietary treatment of a document is made by the manager of the originating component, the person most likely to be acquainted with the value and sensitivity of the information in relation to industry knowledge. Access to such documents within GE is limited on a "need to know" basis.

(7) The procedure for approval of external release of such a document typically requires review by the staff manager, project manager, principal scientist or other equivalent authority, by the manager of the cognizant marketing function (or his delegate), and by the Legal Operation, for technical content, competitive effect, and determination of the accuracy of the proprietary designation. Disclosures outside GE are limited to regulatory bodies, customers, and potential customers, and their agents, suppliers, and licensees, and others with a legitimate need for the information, and then only in accordance with appropriate regulatory provisions or proprietary agreements.

(8) The information identified in paragraph (2), above, is classified as proprietary because it contains detailed damping values for Dryer hood and skirt flow induced dynamic analysis of the design of the BWR Steam Dryer. Development of this information and its application for the design, procurement and analyses methodologies and processes for the Steam Dryer Program was achieved at a significant cost to GE, on the order of approximately two million dollars.

The development of the evaluation process along with the interpretation and application of the analytical results is derived from the extensive experience database that constitutes a major GE asset.

(9) Public disclosure of the information sought to be withheld is likely to cause substantial harm to GE's competitive position and foreclose or reduce the availability of profit-making opportunities. The information is part of GE's comprehensive BWR safety and technology base, and its commercial value extends beyond the original development cost. The value of the technology base goes beyond the extensive physical database and analytical methodology and includes development of the expertise to determine and apply the appropriate evaluation process. In addition, the technology base includes the value derived from providing analyses done with NRC-approved methods.

The research, development, engineering, analytical and NRC review costs comprise a substantial investment of time and money by GE.

The precise value of the expertise to devise an evaluation process and apply the correct analytical methodology is difficult to quantify, but it clearly is substantial.

GE's competitive advantage will be lost if its competitors are able to use the results of the GE experience to normalize or verify their own process or if they are able to claim an equivalent understanding by demonstrating that they can arrive at the same or similar conclusions.

The value of this information to GE would be lost if the information were disclosed to the public. Making such information available to competitors without their having been required to undertake a similar expenditure of resources would unfairly provide competitors with a windfall, and deprive GE of the opportunity to exercise its competitive advantage to seek an adequate return on its large investment in developing these very valuable analytical tools.

I declare under penalty of perjury that the foregoing affidavit and the matters stated therein are true and correct to the best of my knowledge, information, and belief.

Executed on this 1st day of May 2005.

George B. Stramback
General Electric Company