ELECTRIC POWER RESEARCH INSTITUTE

Condenser Pressure Measurement Project: 2013 Advances

3002001089

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Technical Update, December 2013

EPRI Project Manager

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Burns Engineering Services, Inc.

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The following organization, under contract to the Electric Power Research Institute (EPRI), prepared this report:

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This project would not have been possible without Alliant Energy's willingness to host it at their Ottumwa Generating Station. Their staff has been helpful and accommodating. Specifically, Sarah Martz, the site's Thermal Performance Engineer, has been instrumental in her overall engineering understanding, in coordinating, in pursing, and in completing the many steps required to ensure the progress documented in this project.

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ABSTRACT

Condenser pressure has the largest effect on heat rate of any performance parameter in an operating power plant. It is also a difficult parameter to measure, as the steam space in a condenser is quite large and intertwined with bracing, supports, and piping. The steam therein is saturated, containing a significant moisture component, and traveling at very high velocities, approaching the speed of sound.

In 2012, the Electric Power Research Institute (EPRI) initiated a project to establish the optimal sensor configuration and method of measuring an accurate, absolute static pressure within the condenser steam space. The project involved the installation of a multitude of different instruments on an operating steam condenser. The project team employed a robust data acquisition system to ensure sufficient and accurate data was collected, beginning in July 2013, from this large set of instruments and sensors. They also gathered additional plant operating data from the existing plant data historian. These data sets were used in combination to analyze the resulting condenser pressure indications.

Keywords

Basket tips
Condenser backpressure
Condenser performance
Guide plates
Pressure measurements
Pressure sensors

EXECUTIVE SUMMARY

Condenser Pressure has the largest effect on heat rate of any performance parameter in an operating power plant. It is also a difficult parameter to measure, as the steam space in a condenser is quite large and intertwined with bracing, supports, and piping. The steam therein is saturated, containing a significant moisture component, and traveling at very high velocities, approaching the speed of sound.

Monitoring power plant performance and heat rate, attempting to determine optimal timing for actions, requires one to decide whether the condenser pressure is acceptable for a particular set of conditions. An accurate value of condenser pressure provides the basis for timely remedial actions, including determining whether the condenser tubes should be cleaned.

In 2012, EPRI initiated a project to establish the optimal sensor configuration and method of measuring an accurate, absolute static pressure within the condenser steam space. The goal of the project is to establish the minimum number of condenser pressure measurement instruments, where these sensors would be located, what they would consist of, how they would compare to traditional pressure measurements taken above and around the turbine flange, and whether they would exhibit any unusual characteristics or differences as the condenser pressure varied due to seasonal temperature variations and unit loading over a course of a year. This report is a project update on the progress that has been made through October 2013.

A multitude of different instruments were installed on an operating steam condenser. A robust data acquisition system was employed to ensure sufficient and accurate data was collected from this large set of instruments and sensors. Additional plant operating data was gathered from the existing plant data historian. These data sets were used in combination to analyze the resulting condenser pressure indications. Data collection commenced in July 2013.

CONCLUSIONS TO DATE

The results described below are based on the condenser pressure measurements and plant data collected in 2013. This warm weather period of time resulted in operating conditions with comparatively low average turbine exhaust steam velocities of 200 to 300 ft/sec (at the turbine-condenser expansion joint) along with relatively high quality steam (containing some moisture).

1. The most accurate and reliable placement of condenser static pressure taps is between 1 to 2 feet above the inlet end of the tube bundle. With summertime low turbine exhaust steam velocity operating conditions, the location of static pressure taps at the condenser plane is not too important.
2. The study so far has not identified any major difference in the accuracy or reliability of the three gauge types. The basket tips and guide plates are much more costly, more difficult to fabricate in a utility shop and present greater frontal area to the steam flow than the simple pipe tip (a 1/8th inch diameter hole drilled into the downstream side at the end of a small pipe).
3. Except for the confidence and prudent engineering practice that comes from confirmations, the installation of only one pressure type device may be necessary. In the data received to date, the pressure variations are slight and averages of two or more measurements are not needed.

4. At the host site, the plant measured turbine exhaust steam pressure via a basket tip, located about 12 feet above the tube bundle. The instrument is indicating 0.4 in Hg below the other measured condenser pressures. This important gage of plant and turbine performance may be inaccurate and it is recommended its source of error be determined and corrected.
5. At the host site, the turbine exhaust and hotwell temperatures were found to be very different when compared to the installed condenser test static pressure taps. Further analysis will determine if these indications are inaccurate and unreliable.
6. An independent pressure device recently installed was found to provide an unreliable and inaccurate measurement of the condenser pressure compared to the basket tips, guide plate, or pipe tap designs.
7. Pressure and pressure variability differences between device types installed for this project and between zones were small, averaging about 0.04 in Hg and 0.01 in Hg, respectively.
8. The high level of consistency of readings between the different device types showed no clear difference between the devices.

It is emphasized that the above major conclusions are for condensers operating at relatively low steam velocities with high thermodynamic quality steam and so are tentative. During the remaining test program, the study will have the opportunity to examine the reaction, reliability, and accuracy of these popular condenser static pressure tap devices in periods of higher exhaust steam velocities, expected during the cooler ambient temperatures experienced during winter months. The dynamic effects of the exhaust steam velocities are more likely to have an influence on the condenser pressure measurements under those conditions.

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1 INTRODUCTION

Condenser Pressure has the largest effect on heat rate of any performance parameter in an operating power plant. It is also a difficult parameter to measure, as the steam space in a condenser is quite large and intertwined with bracing, supports, and piping. The steam therein is saturated, containing a significant moisture component, and traveling at very high velocities, approaching the speed of sound.

Monitoring power plant performance and heat rate in an attempt to determine optimal timing for operator or maintenance actions requires one to decide whether the condenser pressure is acceptable for a particular set of conditions. An accurate value of condenser pressure provides the basis for timely remedial actions, including determining whether the condenser tubes should be cleaned.

In 2012, EPRI initiated a project to establish the optimal sensor configuration and method of measuring an accurate, absolute static pressure within the condenser steam space. The goal of the project is to establish the minimum number of condenser pressure measurement instruments, where these sensors would be located, what they would consist of, how they would compare to traditional pressure measurements taken above and around the turbine flange, and whether they would exhibit any unusual characteristics or differences as the condenser pressure varied due to seasonal temperature variations and unit loading over a course of a year. This report is a project update on the progress that has been made through October 2013.

Engineering Units

The engineering units used for this study are U.S. customary units. Conversion factors are provided in Table 1-1 for reference.

Table 1-1
Unit Conversions

Parameter	U.S. Customary Unit	SI Unit	Conversion Equation
area	ft^2	m^2	$1\ ft^2 = 0.0929m^2$
	in^2	cm^2	$1\ in^2 = 6.45\ cm^2$
linear	inch	cm	1 inch = 2.54 cm
dimension	foot	meter	1 foot = 0.3048 meter
mass flow	lb_m/hr	kg/s	$1\ lb_m/hr = 0.000126$ kg/s
pressure	inches Hg	kPa	1 inHg = 3.386 kPa
temperature	°F	°C	1 °F = 1.8 * °C + 32

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PROJECT ACTIVITY

Instrumentation and Sensor Installation

Based on the research contractor's (Burns Engineering) test experience using guidance from ASME PTC 12.2-2010 (Condenser Performance Test Code), a total of 15 pressure sensors of the types that are typically and often used by utilities were designed, specified, fabricated, and installed in an array of various locations at an average of 18 inches above the second pass of the most western tube bundle of Alliant Energy's Ottumwa, Unit 1-A condenser.

During 2012, these sensors were installed inside the condenser by Alliant Energy's mechanical contractor, and inspected by Burns Engineering for proper welding and compliance with the designs to ensure physical reliability. These sensors and their relative locations in the condenser are depicted in Figure 2-1. Additional details on the particulars of the sensors and their design is provided in the 2012 EPRI project Technical Update Report [1] on this project. Figures 2-2, 2-3, and 2-4 contain photographs of the three key sensor types installed in the Ottumwa steam condenser as part of this project, basket tips, guide plate, and pipe tip, respectively.

In addition to the condenser pressure sensing devices installed for this project, two additional pressure sensors were monitored and the results were included in the analyses. The first is the plant process gage, a permanently installed instrument with a basket tip in the condenser steam space, identified as PlantP_Shell 1a. The second was an independent third party instrument, recently installed with a unique pipe tip in the condenser steam space, identified as PlantP_CND 1A.

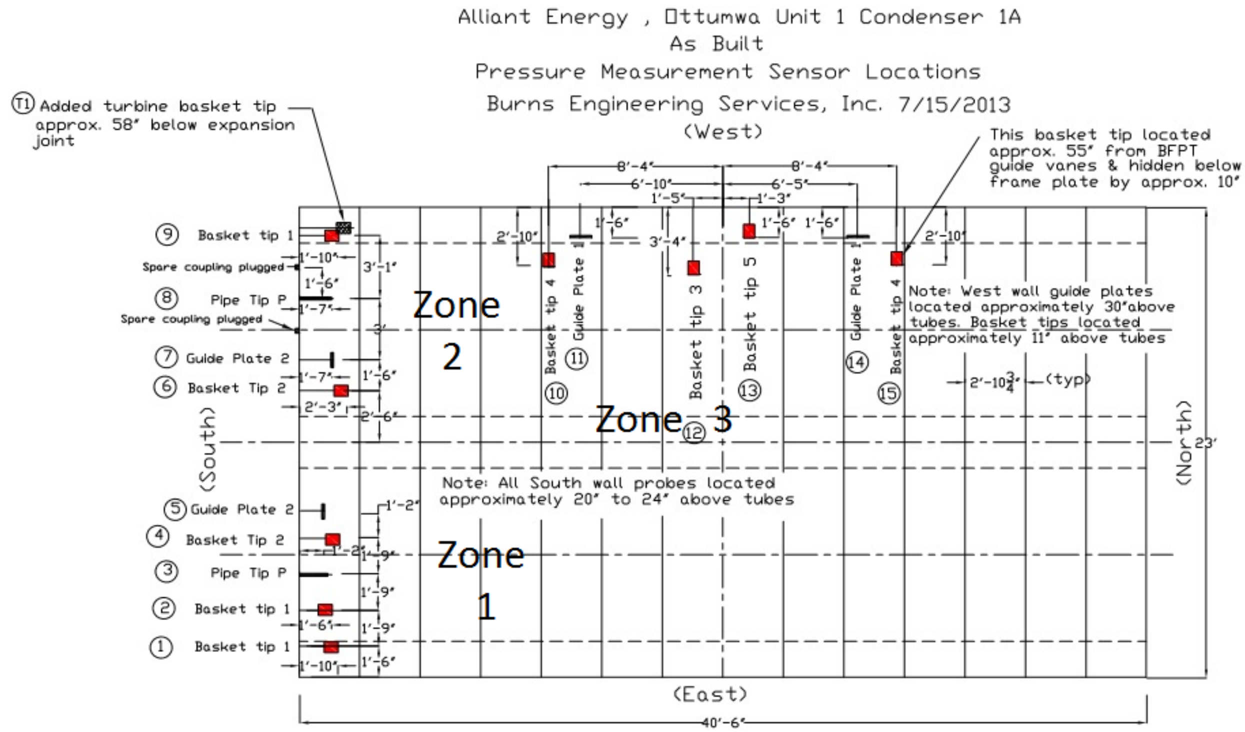

Figure 2-1
Pressure Sensors and Locations

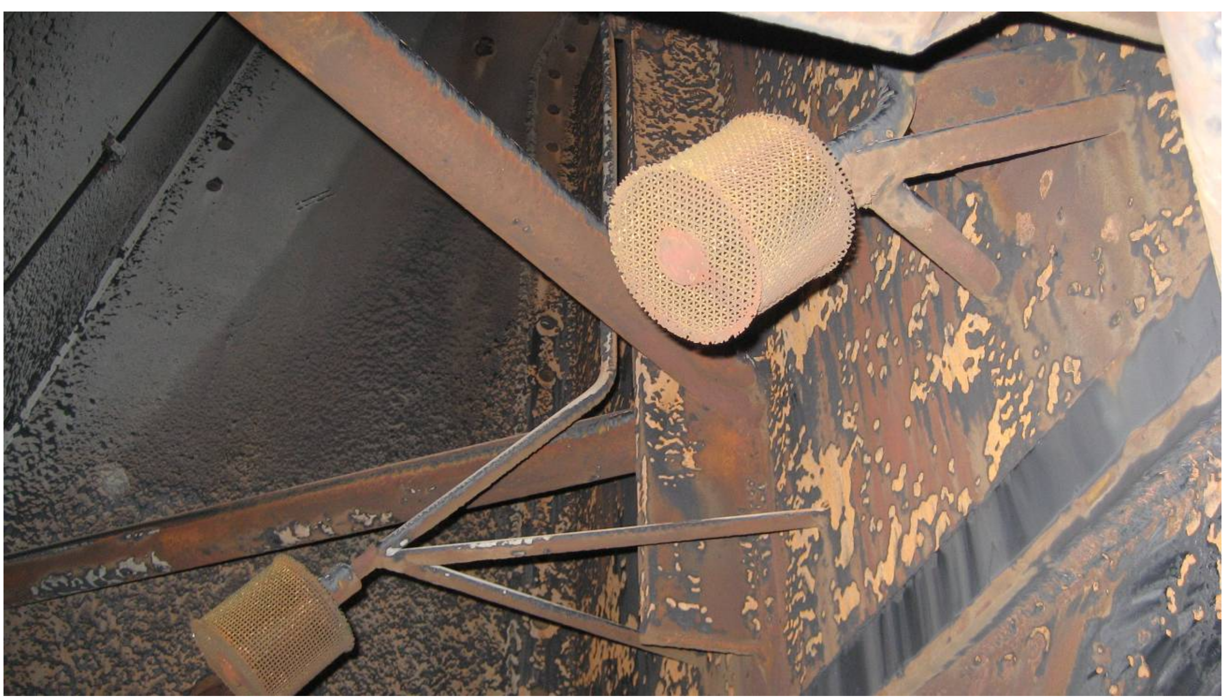

Figure 2-2
Basket Tips

Figure 2-3
Guide Plate

Figure 2-4
Pipe Tip

Plant and Condenser Description

The steam condenser on which the tests were conducted serves the 731 MW Ottumwa Generating Station and was designed and manufactured by De Laval in 1975. It is an opposed flow, single pressure 367,000, square feet two-pass heat exchanger, comprised of about 33,500 1 inch 20 BWG, 90-10 copper-nickel tubes. The tubes are 42 ft long and contained in two identical shells, designated A & B. The tubes are designed to pass 248,000 gallons per minute circulating water received from cooling towers. The condenser was designed to condense 4,102,000 lb_m/hr of steam at a shell pressure of 3.99 in Hga with an 85% cleanliness factor and an inlet circulating water temperature of 93°F.

Instrumentation and Data Acquisition

A Scanivalve™ system was evaluated and its capability was considered very suitable for the pressure measurement and recording portion of the project. The Scanivalve system was purchased for use on this project for installation by Alliant. The specific model is capable of measuring up to 16 different pressures more frequently than once per second. The manufacturer claims an accuracy of better than ±0.2%. The device automatically purges each condenser pressure sensor line and immediately thereafter quickly collects the pressure data to ensure no interference from potential condensate buildup in the sensor line. It can operate automatically for an entire month reading all 15 pressure sensors at least every 4 minutes.

Reducing the uncertainty of the results is a key benefit of utilizing from this one device instead of separate pressure instruments. The results from those 15 sensors can be readily compared as any instrument bias existing in the measurements should be equal for all 15.

By early 2013 an appropriate NEMA enclosure had been selected by Alliant to house the data acquisition computer and the Scanivalve pressure data measurement device. To provide the necessary continual downward slope of the sensor tubing to the condenser penetrations, the cabinet was installed in a corner on the turbine deck. Electrical power and plant compressed air were routed to the enclosure. Flexible plastic tubing from the instrument connections was routed into the enclosure by the end of February. Meanwhile, a list of the DCS Ottumwa plant data was also developed by the project participants to provide additional perspectives on plant conditions at the time of the condenser pressure test measurements.

The Panasonic Toughbook™, a laptop computer that would withstand the high summer temperatures of the steam turbine operating floor inside the NEMA cabinet, was then selected to record the output from and control the Scanivalve. This computer was in place by the beginning of June. The Scanivalve software was loaded as well into the computer by the beginning of June. It was however decided that before any data is collected, to ensure a low system test uncertainly of under 0.05% of full scale, that it would be prudent to send the Scanivalve back to the factory for an updated calibration. This was accomplished and an engineer from Scanivalve visited Ottumwa to aid in the final installation and the initial operation of the equipment.

In July 2013 formal data collection started via the Scanivalve and Toughbook system. The data collected included 40,000 pressure measurements per month from the Scanivalve system in addition to another 200,000 measurements of related cooling system and general plant data. That additional, larger set of data was acquired from the plant's EtaPro™ Performance Monitoring system to provide plant operating conditions. These data sets were used in combination to analyze the resulting condenser pressure indications.

It is important to note that the integration and the installation of the many elements of this data acquisition system was no simple matter. It was evident that the staff of Ottumwa, specifically in the form of Ms. Sarah Martz, was instrumental in ensuring successful data collection for this project.

Data Reduction and Analysis

To evaluate the different condenser pressure sensor types during the expected changes in circulating water temperatures which result in seasonal changes in condenser pressure and turbine exhaust steam velocities, the data collected was sent monthly to Burns Engineering for statistical analysis, trending, and observations as described more extensively later in this technical update report. The amount of data used in these periodic analyses is not trivial. From the fifteen sensors installed specifically for the project, data was collected every 4 minutes for the duration of the project. An additional, larger set of data was acquired from the plant's EtaPro Performance Monitoring system to provide plant operating conditions, also to be used in the analysis of the condenser pressure data.

Monthly and seasonal reports were compiled by the consulting company / research contractor on the test condenser pressure measurements and also included related key Ottumwa plant cooling system measurements. At this time, the tests, monthly data and seasonal analysis are projected to continue into July of 2014.

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MEASUREMENTS AND ANALYSES

Introduction

Data described in this report was recorded for the 88-day period of July 12th 2013 through October 10th 2013, with the exception of a 10-day planned unit shutdown between September 16th and September 26th 2013 and several other brief periods. Data from the fifteen Scanivalve devices (taken at 4 minute intervals) and the plant's DCS EtaPro database (taken at 5-minute intervals) was sorted, indexed, and combined to create a master dataset that contains pressure and selected other plant-related data in 5600 twenty-minute intervals. Two plant pressures determined by converting temperature data using steam tables as well as two direct pressure estimates from plant data were pulled from the EtaPro database and combined with the fifteen Scanivalve pressures to result in a total of nineteen independent pressure estimates for the comparisons.

No "true" pressure was identified for this or any steam condensers operating in power plants today. This project itself is to help identify the optimal placement and sensing method for future use in the industry. That said since this test project contains no "master" gauge, or standard certified pressure sample for reference, the qualities of consistency and reliability in the pressure estimates and the concept of consensus measurements within categorical groups will be leveraged to arrive at judgments of which of the nineteen pressure estimates and which categorical groups (i.e.-gauge types and measurement locations) are most favorable. In order not to provide a false sense of confidence, the term "estimate" has been used throughout the report referring to the pressure indications acquired as part of this project.

Table 3-1
The Nineteen Pressure Sensors

Label of Pressure Estimate	Source Location	Device Type
Scanivalve Channel 1	Condenser Zone 1	Basket Tip
Scanivalve Channel 2	Condenser Zone 1	Basket Tip
Scanivalve Channel 3	Condenser Zone 1	Pipe Tip
Scanivalve Channel 4	Condenser Zone 1	Basket Tip
Scanivalve Channel 5	Condenser Zone 1	Guide Plate
Scanivalve Channel 6	Condenser Zone 2	Basket Tip
Scanivalve Channel 7	Condenser Zone 2	Guide Plate
Scanivalve Channel 8	Condenser Zone 2	Pipe Tip
Scanivalve Channel 9	Condenser Zone 2	Basket Tip
Scanivalve Channel 10	Condenser Zone 3	Basket Tip
Scanivalve Channel 11	Condenser Zone 3	Guide Plate
Scanivalve Channel 12	Condenser Zone 3	Basket Tip
Scanivalve Channel 13	Condenser Zone 3	Basket Tip
Scanivalve Channel 14	Condenser Zone 3	Guide Plate
Scanivalve Channel 15	Condenser Zone 3	Basket Tip
Plant P_Shell 1a	EtaPro Column M	Basket Tip
Plant P_CND 1A	EtaPro Column AU	Indepdnt Gauge
Plant P_hotwell	EtaPro Column O*	Thermocouple
Plant P_exhaust hood	EtaPro Column U*	Thermocouple

* - These estimates are calculated from temperature data.

A description of the sensor bases of the nineteen pressure estimates (fifteen Scanivalve pressure gauges of the study plus the four plant-derived pressures from the EtaPro data) is provided in Table 3-1. Plots of the nineteen pressure estimates at 20-minute intervals over the 78-days of operation are shown in Figure 3-1 on the following page.

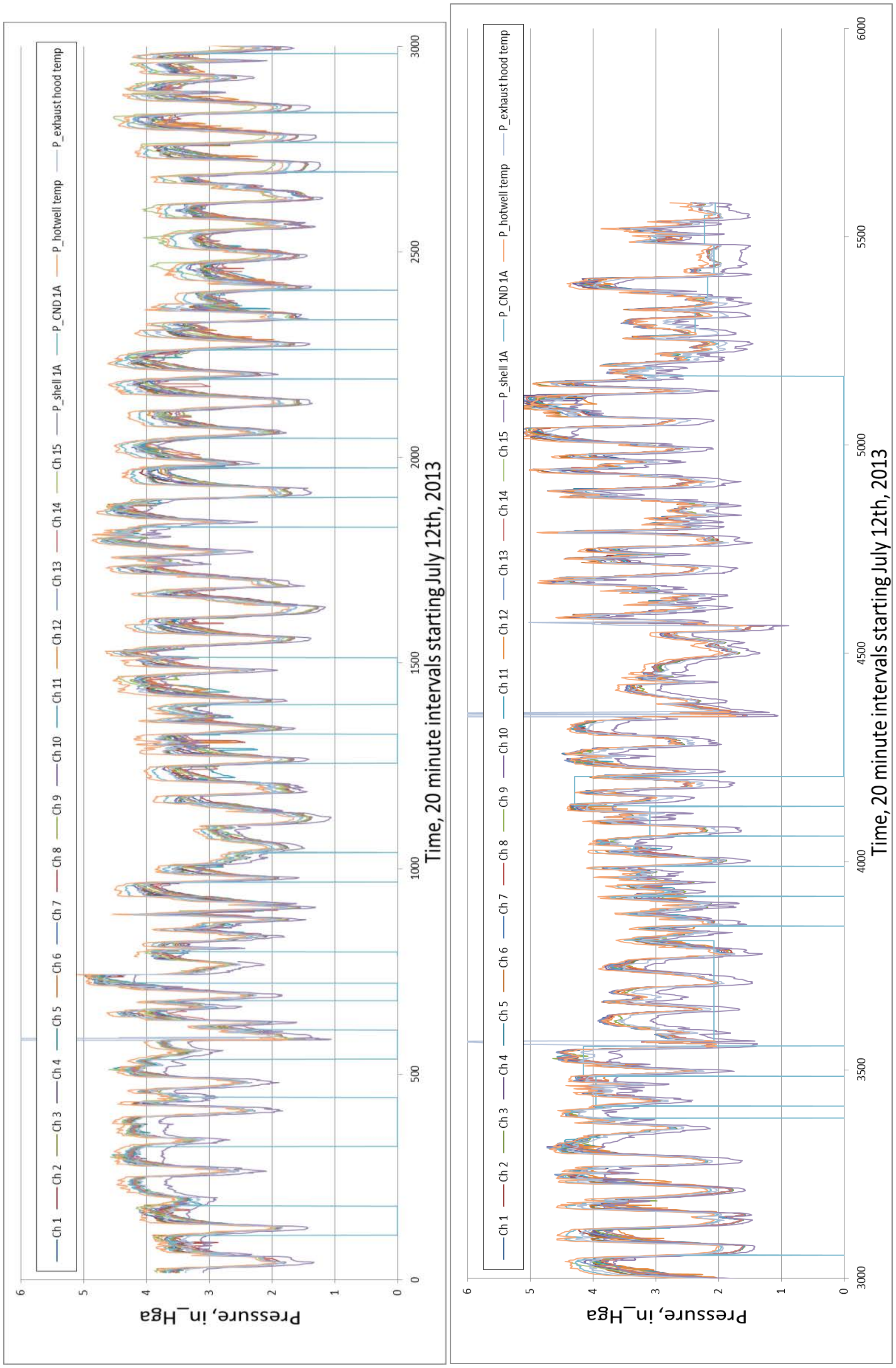

Figure 3-1
A Time-Series Plot Of Condenser Pressure Estimates For The 78-Day Master Data Set

Detailed Data Observations and Anomalies

Before launching into statistical comparisons and analyses of these estimates, the following observations were made from the master spreadsheet itself and the plots of Figure 3-1:

- The 88 day period during which the sensors were recording data included several intervals of plant outages during which data from the sensors departed from the normal pressure and/or temperature ranges. The largest of these was the 10-day planned outage when the unit was shut down from September 16th through 26th. Data from such periods was removed from the analysis dataset (and from Figure 3-1) to keep the focus on gauge performance during the normal plant operating regime.

- Channel 15, recording the pressure from a basket tip device in Zone 3, ceased functioning on August 23rd at 6:40 pm. An investigation by the Scanivalve equipment supplier revealed a failed resistor in its excitation circuit. The supplier repaired the sensor and it returned service after the data collection for this report had ended.

- The Independent-sensor device, labeled "P_CND_1A", produced what is labeled as "Bad Input" over 39 separate periods of time comprising in total about 26% of the overall 80-day study. After August 15th, it also intermittently exhibited a discretization error, i.e., it reported a fixed pressure value over long periods of time (hours) while the other 18 pressure estimates were indicating pressure varying within the condenser with each measurement. This malfunction occurred over an additional 12% of the 80-day recording period). Plant personnel suspect a communication issue between way the device and the EtaPro data recording system and are working to correct the problem.

- Erratic readings (dips well below the consensus pressure range) were reported on a couple of occasions by Channel 14- the guide plate device in Zone 3.

- Erratic values (high pressure spikes at approximately readings 550, 3550, and 4300) were also reported by the pressure derived from the plant exhaust hood temperatures.

- A closer look at the curves of Figure 3-1 (such as the example in Figure 3-2) show the data from some devices takes small excursions from the remainder of the data, particularly at times when the condenser pressure is higher. This occurred most often for certain estimates (the Independent device, Pshell 1A, and channels 8, 11, 12, and 14) which tended to temporarily differ from the pressure estimates of the other gauges.

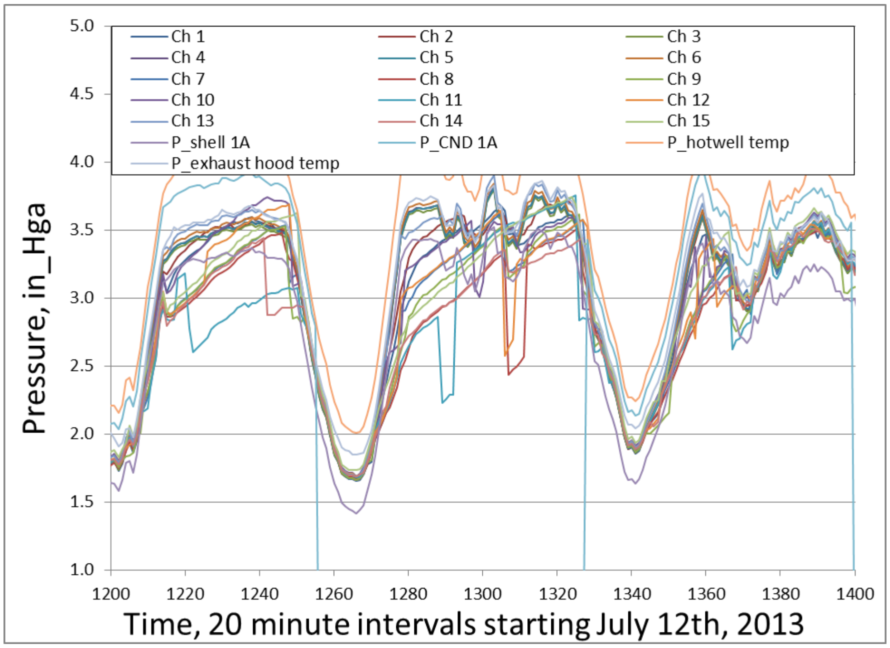

Figure 3-2
Close-Up On A Section Of The Master Datasheet's Time-Series Plot

Pressure Estimate Data Analysis

Statistical Comparisons

Statistical tools used to evaluate the 19 condenser pressure estimates (and the groups later in the report) include the following:

- Mean: The statistical average calculated by summing all individual values and dividing by the number of individual values.
- Median: The "center value" of a group of individual values which is smaller than half the individuals in the group (not including itself) and larger than half the individuals in the group (again, not including itself). If the group has an even number of individuals the mean of the two closest center values is taken as the median.
- Standard Deviation: A statistical measure of the variation of a population about its average. It is calculated by taking the square root of the sum-squared difference of each value with respect to the mean value and dividing it by the square root of the sample size minus 1.
- Variance: Simply the square of the standard deviation.
- Range: The maximum value minus the minimum value of a dataset. Range is a simple measure of the variation of a population about its average. Since in the usual data plots, the condenser pressure due to heat load and inlet water temperature from the cooling tower vary appreciably, this is reflected by the calculated ranges and standard deviations.
- T-test: A statistical tool to determine within a given confidence level whether the mean values of two populations can be considered statistically different. A "paired" t-test takes

advantage of situations where individuals in the populations are linked, such as in the case where pairs are estimating the same true value.

- Control Chart (Xbar-R type): A plot of a series of data that separates the data into subgroup and displays the mean value of each subgroup and the range within each subgroup over time. Control limits are calculated for both the subgroup means and subgroup ranges so values that exceed expected ranges and trends can be identified.
- Control Limit: The calculated limit outside which a normal datapoint is not expected to fall. For the control charts of this report, this limit was set at 3 times the expected standard deviation of the population.
- p-value: A calculated statistical parameter that (in most applications) represents the probability of attaining a more extreme (or different) value by random chance. A p-value below a presupposed confidence level (often 0.05 is used) indicates that a difference can be considered statistically significant.
- R^2_{Adj}: A statistical measure of goodness-of-fit, it is the level to which a regression explains observed variation in the data. The basis of this is R^2, which is the sum of squares in the modeled regression divided by the total sum of squares of the data. The "adjustment" is made to offset the effect of the number of predictor variables in the regression model.

Calculated Individual Estimate Condenser Pressure Statistics

This analysis utilized the Means, Standard Deviations, and Ranges of the data collected. Those statistical measures determined directly from the columns of the master data comprise Table 3-2. Note that the standard deviations shown represent all pressure variations for that channel independent of their causes rather than variation due to error within the estimates. Variations in ambient temperature and unit load (condenser heat duty) are examples of uncontrolled drivers of the afore-mentioned pressure variations.

Table 3-2
Channel by Channel Pressure Statistics

	Ch 1	Ch 2	Ch 3	Ch 4	Ch 5	Ch 6	Ch 7	Ch 8	Ch 9	Ch 10
average	3.10	3.12	3.15	3.16	3.14	3.18	3.07	3.02	3.05	3.15
std dev	0.79	0.79	0.81	0.81	0.80	0.82	0.77	0.76	0.77	0.80
range	3.77	3.80	3.94	3.94	3.80	4.00	3.90	3.82	3.79	3.91

	Ch 11	Ch 12	Ch 13	Ch 14	Ch 15	P_shell 1A	P_CND 1A	P_hotwell temp	P_exhaust hood
average	3.05	3.07	3.18	3.04	3.24	2.76	3.18	3.42	3.15
std dev	0.77	0.77	0.82	0.76	0.77	0.78	0.91	0.82	0.82
range	3.78	3.84	3.95	3.82	3.62	3.59	5.27	3.66	9.37

Clearly, two of the estimates are far outside the consensus (median) pressure of the estimates. The shell pressure P_shell 1A averages about 0.38 in Hg lower than the other values, and P_hotwell temp averages 0.28 in Hg higher. All other estimates were within ±0.10 in Hg of the consensus (median). Note that the stated equipment calibration accuracy of the fifteen Scanivalve sensors (±0.05% of full scale) explains only about 2% of this ±0.10 in Hg difference in means. Basically, these indicate that the plant measured turbine exhaust pressure, represented by P_shell 1A, runs low by 0.4 in Hg and using the hotwell temperature as a gage of the condenser pressure will provide an indication that may be 0.25 in Hg higher than it actually may be.

Variation in measurement systems can indicate measurement error. The standard deviation describing the variation of the Independent device P_CND 1A, at 0.91 in Hg, was significantly higher than that of the other estimates, which all fell between 0.76 and 0.82 in Hg. The range of the converted P_exhaust hood, at 9.37 in Hg, and the Independent device, at 5.27 in Hg were the highest of this data set. The other seventeen gauges fell between 3.77 and 4.00 in Hg. Basically, these ranges suggest that the exhaust hood temperature at Ottumwa and the Independent pressure measurement were less reliable estimates of the condenser pressures than the others during this time period.

Taking the total measured standard deviation as σ_{total} and the actual real pressure variation as σ_p, the measurement variation associated with each estimate σ_m is given by:

$$\sigma_m = ((\sigma_{total}^2 - \sigma_p^2))^{1/2}$$

Assuming that pressure variation throughout the condenser is uniform and equal to the lowest level of variation exhibited by the pressure estimates, the 0.76 in Hg standard deviation of channel 14, the level of measurement error in the pressure estimates due to variation can be computed. In this case, σ_m ranges from the 0.00 in Hg of channel 14 to 0.51 in Hg for the Independent device P_CND_1A. The associated typical error of a given measurement from the devices resulting from this variation can then be calculated to range from 0 in Hg to 0.35 in Hg. This error would be in addition to whatever offset/calibration error was associated with the offset of the mean value of measurements from the target (true value).

If instead, one were to assume that the estimate with the lowest standard deviation contains 5% measurement variation and the others increase from that norm, σ_m for the nineteen estimates would range from 0.17 in Hg to 0.54 in Hg and the typical error in measurement would range from 0.11 in Hg (channel 14) to 0.36 in Hg (Independent).

Statistical Significance Testing Results

For any further comparisons between these populations regarding their differences to be valid, it was necessary to ensure that the above populations were actually statistically independent of each other. The paired t-test was used to determine the probability (indicated by a p-value) that the differences these nineteen estimates were random variation. With nineteen separate populations, there were 171 (equal to 18+17+16…+1) possible combinations, but only those that were close in mean needed to be evaluated.

P-values for paired t-tests show that pressure data from the 163 of 171 possible combinations of the 19 channels are statistically independent. The p-values of such tests calculate the probability that observed differences in the data could have been produced through random variation in the data: values below 0.05 are interpreted as demonstrating real rather than random differences.

A statistical difference does not guarantee a practical difference (which will be needed to initiate action based the conclusions), but it does validate further analysis to better understand and explain these populations in relation to each other.

Group Data Analysis

Calculated Group Condenser Pressure Statistics (Means, Standard Deviations)

As with the individual estimate statistics, variation, represented by standard deviation in this case, includes, and in fact, is dominated by, the real changes to pressure within the condenser over time.

Table 3-3
Grouped Pressure Statistics

Zone 1	Zone 2	Zone 3		Basket Tips	Guide Plates	Pipe Tips
3.13	3.08	3.12	Avg Pressure	3.14	3.07	3.08
0.80	0.78	0.78	Avg Std Dev	0.79	0.77	0.79

When the fifteen Scanivalve estimates are grouped into three zones and their statistics are calculated, referring to Table 3-3, that on average, Zone 2 had the lowest pressure, then Zone 3, and then Zone 1, but the range of difference was relatively small, at 0.05 in Hg. The standard deviation of Zone 1, at 0.80 in Hg, was ever so slightly higher than the other two zones, both at 0.78 in Hg. None of these differences indicate an advantage in pressure measurements based on the condenser zone. Basically, this indicates static pressure instrumentation can be located anywhere at a few feet above the condenser tube bundle when the exhaust steam velocities are relatively low. This outcome will be re-evaluated when the high steam velocities occur concurrent with lower ambient temperatures of winter. Refer to Figure 2-1 for delineation of the three zones.

Grouping the fifteen Scanivalve estimates into device types, on average, Guide Plates and Pipe Tips (3.07 and 3.08 in Hga, respectively) are reporting slightly lower pressures than Basket Tips, at 3.14 in Hga. These differences are not insignificant, but without a known “true” value for reference, it is not possible to judge which of these averages is more accurate. The standard deviation of Guide Plates, at 0.77 in Hg, was just slightly lower than the other two zones, both at 0.79 in Hg. None of these differences indicate an advantage in pressure measurements based on device type.

Look-Across Range Comparison for Zone

The Look-Across Range is the maximum minus the minimum reported pressure value in a group measured at any given moment in time. The average of this range for each group over the entire 78-day recording period is reported below. These values are an indication of the level of consistency in pressure reported within each group, with smaller look-across range indicating an estimate possessing better consistency. Since the groups have differing numbers of members, a statistical adjustment was used to standardize these values to produce a meaningful comparison.

Table 3-4
Look-Across Range Comparisons for Zones

Zone 1	Zone 2	Zone 3	
0.09	0.20	0.28	Avg Lookacross Range
5	4	6	Sample size in group
0.04	0.10	0.12	Standardized L/A Range

Referring to the results compiled in Table 3-4, Zone 1 devices report substantially lower average look-across ranges (i.e., more consistent pressures) than devices in Zones 2 and 3. This difference amounts to over a 60% reduction of variability compared to the other two zones over the entire 78-day recording period, which is a significant difference.

At each monthly update of the data, the look-across range for the devices in Zone 1 was far better than that for the devices in the other zones. This could indicate that Zone 1 pressure is inherently more stable or consistent than the others and most likely indicates there is a clear preference to locating condenser pressure sensors at the inlet end of a condenser tube bundle.

At the end of this data collection period the Scanivalve device was sent for repair and recalibration. Upon its return to service the group will investigate with the OEM the unlikely possibility that a sequential calibration started at that end of Scanivalve to produce more accuracy for those nearby channels or any other calibration scheme that would introduce a bias into certain channels.

Look-Across Range Comparison for Device Type

Table 3-5
Look-Across Range Comparisons for Devices

Basket Tips	Guide Plates	Pipe Tips	
0.30	0.19	0.15	Avg Lookacross Range
9	4	2	Sample size in group
0.10	0.09	0.11	Standardized L/A Range

After standardizing for group sample size, the Guide Plates have a slightly lower average range than Basket Tips and Pipe Tips have a slightly higher range than Basket Tips. Refer to Table 3-5 for the specific values. The reported ranges of device types after standardization only vary by about 10%, which is probably not a significant practical difference. This result indicates that at least at relatively low summer turbine exhaust velocity levels of comparatively high thermodynamic steam quality, a downstream side, small, single drilled hole static pressure tap of about 1/8 inch diameter at the end of a piece of pipe is as consistent as a basket tip. Since currently basket tips cost about $700 each, the simple pipe tap hole has a major cost advantage and can be easily fabricated in a utility maintenance shop.

Pressure Readings During High and Low Load Operation

Comparing the condenser pressure measurements at times of approximate high and low heat loads with its associated steam flow, was included because it could provide insight to the extent to which high velocity steam flow is affecting the pressure reading of each gauge. Hence, data was sorted into groups focused on the high load and low operating periods: median pressures of the 18 gauges reading below 2.5 in Hga composed the low load data set and those above 4.0 in Hga composed the higher-load data set. Numerical data for rows with median consensus pressures between 2.50 and 4.00 in Hga inclusive were removed from the dataset for the purpose of this analysis in order to provide a clear distinction between the regimes.

Figure 3-3 is a plot showing the high-load and low-load pressures from the master dataset plotted against intake circulating water temperature (average of 1A and 1B shells).

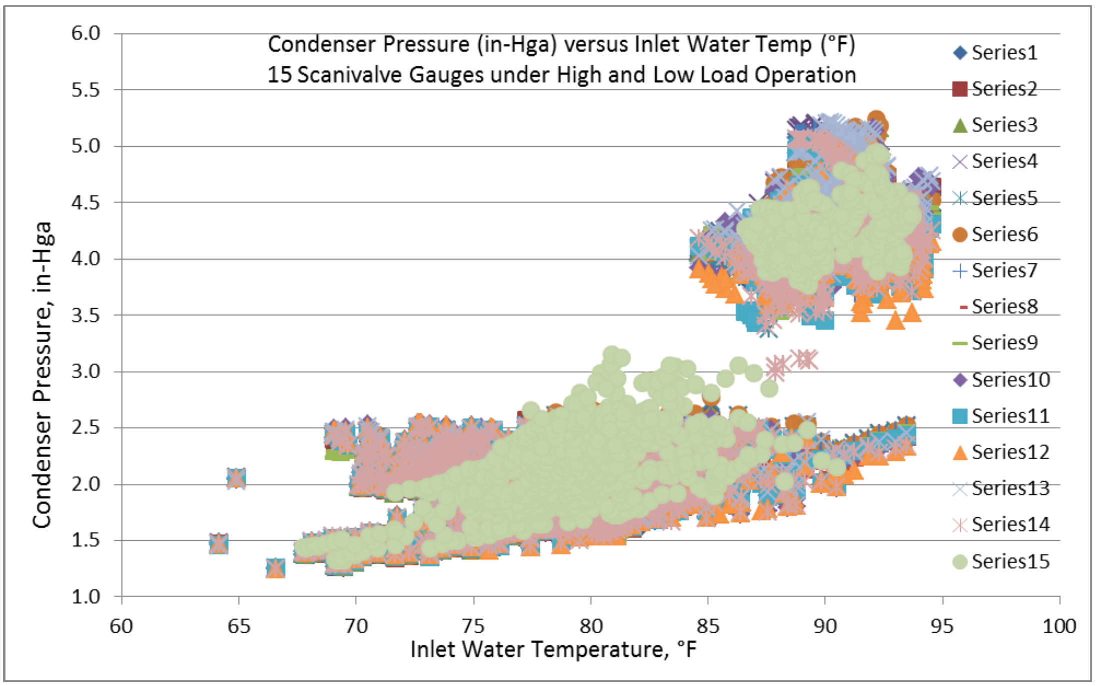

Figure 3-3
Condenser Pressure During Low And High Load Operation Vs Inlet Water Temperature

Low Load Averages and Offset

Table 3-6 provides the average pressure for each channel at low unit load and offset difference between this value and the 2.04 in Hga median value of the 14 Scanivalve channels.

Table 3-6
Pressure Averages and Offset at Low Unit Load

	Ch 1	Ch 2	Ch 3	Ch 4	Ch 5	Ch 6	Ch 7	Ch 8	Ch 9
average	2.03	2.04	2.04	2.05	2.05	2.06	2.04	2.01	2.02
offset	-0.02	-0.01	0.00	0.01	0.00	0.01	0.00	-0.03	-0.03

Ch 10	Ch 11	Ch 12	Ch 13	Ch 14	Ch 15	P_shell 1A	P_CND 1A	P_hotwell temp	P_exhaust hood
2.06	2.04	2.04	2.07	2.03	2.16	1.72	2.23	2.32	2.18
0.02	0.00	0.00	0.03	-0.01	0.12	-0.33	0.19	0.27	0.14

High Load Averages

Table 3-7 provides the average pressure for each channel at high unit load and adjusted averages after applying the low load offset determined previously.

Table 3-7
Pressure Averages and Offset at High Unit Load

	Ch 1	Ch 2	Ch 3	Ch 4	Ch 5	Ch 6	Ch 7	Ch 8	Ch 9
average	4.22	4.25	4.30	4.30	4.26	4.34	4.21	4.15	4.20
offset @ lo	-0.02	-0.01	0.00	0.01	0.00	0.01	0.00	-0.03	-0.03
adjusted avg	4.24	4.26	4.30	4.29	4.25	4.33	4.21	4.18	4.22

Ch 10	Ch 11	Ch 12	Ch 13	Ch 14	Ch 15	P_shell 1A	P_CND 1A	P_hotwell temp	P_exhaust hood
4.31	4.18	4.19	4.35	4.16	4.25	3.79	4.26	4.50	4.19
0.02	0.00	0.00	0.03	-0.01	0.12	-0.33	0.19	0.27	0.14
4.29	4.19	4.20	4.33	4.17	4.13	4.12	4.07	4.23	4.05

The average values for the 15 Scanivalve channels at low load operation fall within 0.15 in Hg of each other (from 2.01-2.16 in Hga), but most of this variation is due to the high average of channel 15, which malfunctioned for about 10 days before it failed. The offset shows the inherent pressure difference of each measurement channel and should be zero at no load. With the exceptions noted below, the offsets are very small. This value would be 0.05 in Hg if only channels 1 through 14 were included. Under high load conditions the variation is 0.20 in Hg (from 4.15 to 4.35 in Hga). Assuming the channel 15 data to be faulty and discounting the results therein, the difference in the range of averages for the other 14 channels between high and low load operation may reflect an initial sensor calibration point nearer the low-load condition and error which compounds in spanning to higher values, or just the inherently more variable pressure conditions (dynamics) at higher loads and higher steam velocities.

In both load regimes, P_shell 1A, the plant reading of turbine exhaust pressure is averaging well below the other 18 pressure estimates. The pressure estimates based on the other three plant values also all fall outside the range of the Scanivalve pressures at low load operation. Under high load, P_Hotwell remains well above the other channels but the Independent device P_CND 1A and P_exhaust hood fall amongst the Scanivalve values. These differences may reflect true pressure variations at their respective measurement locations or inherent error in the gauges. The relationships are expected to be considered more exactly during the coming months.

Calculating an offset based on the average pressure at low load operation and applying it to the high load averages (basically zeroing out any initial set-point bias at low load) results in very slight changes (±0.03 in Hg) to the high load averages for channels 1 through 14. The range of the average values of these channels after adjustment changes from the 0.20 in Hg described above to 0.16 in Hg (i.e., - highest channel 4.33 minus lowest channel 4.16). Including the averaged data from channel 15 (4.13 in Hg) in the analysis would increase this range back to 0.20.

Using the low offset described above on the four plant based estimates has differing effects. The adjusted mean for the shell pressure and hotwell temperature based estimates are brought into the range of the Scanivalve readings by applying the offset, while the condenser pressure and exhaust hood pressure have been dropped further out of the Scanivalve range by the adjustment.

Condenser backpressures were still relatively high and representative of late summer conditions. As a result, the average exhaust steam velocities (~150 to 200 ft/sec) were relatively moderate and would not be expected to have a large dynamic influence on the value of static pressures measured by the various devices in their various locations. At low loads such as at night, they would be expected to have even less difference, one from another.

A comparison of condenser pressures under low and high load conditions confirmed smaller pressure differences under lower loads and higher variability between pressure estimates at higher loads.

Regression Analysis

To consider if the location zone and/or gauge type would have dominant effect on any choices a utility would have when planning to instrument a condenser for performance monitoring, a regression model was created for the condenser pressure based on device type and zone. The regression equation based on data taken at approximately 8-hour intervals over the course of the 78 days of operating history is:

Condenser Pressure (in Hg_abs) = 3.20 - 0.0231 Zone* - 0.0264 Gauge Type*

where Gauge Type* = 1 for Basket Tips, 2 for Pipe Tips, and 3 for Guide Plate Devices, and
Zone* = 1 for Zone 1, 2 for Zone 3, and 3 for Zone 2.

Regression analysis observations include:

- R^2 was 0.1% and R^2 adj was 0.1% for the regression model, indicating the regression's modeling factors alone are poor predictors of overall pressure (i.e., - pressure changes in the data are due to other variables than zone and device type: they are due to actual changes in pressure in the condenser).

- The P-value of 0.10 for the overall regression indicates the overall model is not clearly affected by the modeled variables in the data.
- The P-values of 0.17 and 0.10 for the gauge type and zone variables, respectively, indicate the effects of each are not evident in the data: there is a significant chance that random differences could explain them.

This regression model is not capable of explaining the effects of zone and gauge type on pressure or useful for planning because the variable it is modeling (pressure) is so heavily influenced by factors outside zone and gauge type.

Trend Analyses

The offset of each of the 15 Scanivalve devices from the group's median value was plotted on a control chart by daily average, grouped in 4-hour intervals. These fifteen plots were reviewed for control issues and for notable trends over the 78-day study period; the following observations were made:

- In the 78-days tested, most gauges had a modest (less than 6) number of daily averages outside the control limits established by the measured variability. The exception to this was channel 15, which had fifteen points outside of control limits owing to a marked increase in offset from the median value starting with day 33. Channel 15 remained high from that point until it failed on day 43. The increase due to malfunction necessarily will force the Zone 3 and Basket Tip group averages higher. As was noted, this Scanivalve measurement channel is being repaired by the manufacturer during the recalibration so should not be an issue in the future.
- Most curves had long periods (from 9 to 26 days) in which their means flattened out rather than randomly varying within the full control limits. In most cases, this flattening was accompanied by a reduction in the range at the same interval (i.e., 4-hour averages were not varying as much as expected either).
- Channel 14 mean pressure appeared to be on a slight upward trend starting in day 41 and continuing through the end of the study period in day 78.

Figure 3-4 contains control charts plotted against the median for daily averages grouped by 4-hour intervals were also plotted for each of the three Zones and each of the three device types to identify any trends in the data over time.

Figure 3-4
Control Charts of Average Daily Pressure Offset Grouped Into 4-Hour Periods

The following observations regarding zone group pressure trends were made from the charts in Figure 3-4:

- Zone 2's variation within the day, with an average range of 0.08 in Hg, is lower than the other two which are both above 0.11 in Hg. Since Zone 2 has fewer gauges in it than Zones 1 and 3, this difference is probably unimportant.

- Zone 3 contains spikes around days 35 and 43, coinciding with the rapid rise and failure of Channel 15, respectively.
- Zone 2 shows a sharp dip in its mean and spike in its range around day 39. This was traced to a spike in channel 7 at this time.
- No severe trends in the zones are evident, but zones 2 and 3 may be showing a slight upward trend starting around the day 40 at the midpoint of the above plots. This possible trend will be monitored in future data.

The following observations regarding device type group pressure trends were made from the chart:

- Basket Tips display the rise, elevated operation, and spike associated with the end of channel 15 in days 35-43. They also exhibited very flat, stable means and ranges from about days 50 through 60.
- Guide Plates show a spike that matches the day 39 Zone 2 data, whose cause was traced to channel 7, the guide plate device installed in Zone 2. The cause of the spike in channel 7 is unknown.
- Basket Tips, with an average within-day range of 0.06 in Hg, came in lower than Pipe Tips and Guide Plates, at 0.07 and 0.10 in Hg, respectively.
- For the last 30 days of the period, both Guide Plates and Pipe Tips seemed to provide data somewhat above their mean-lines. This is possibly a slight upward trend, which will be monitored into the future to identify the cause(s).
- No clear conclusion referencing one device over the others can be made from the device type control charts except that the measurements are relatively stable during this data collection period.

Procedural Notes

- All analysis in this summary was performed using unconditioned data. No attempt was made to separate real pressure differences over time from differences due to device type or zone. While this resulted in higher reported standard deviations for the data's summary and group statistics and a reduction in the clarity of the regression model, it did not appear to hamper the clarity of group statistics, look-across comparisons, or statistical significance.
- All analyses were performed on data taken over the full 88-day recording period from July 12th through October 10th (except during the September 16th through September 26th planned outage shutdown period and a couple brief shut down intervals). Except where noted on data time intervals these were every 20 minutes.

4

KEY CONCLUSIONS AND RECOMMENDATIONS

Table 4-1
Performance Data from the 19 Pressure Estimate Sources

Pressure Estimate	Source Location	Device Type	Notes on Estimate / Gauge Function / Anomolies	Pressure, in-Hga		Notes on July 12 to October 10 Pressure Readings
				Mean	Std Dev	
Channel 1	Cond Zone 1	Basket Tip		3.10	0.79	No unusual behavior.
Channel 2	Cond Zone 1	Basket Tip		3.12	0.79	No unusual behavior.
Channel 3	Cond Zone 1	Pipe Tip		3.15	0.81	No unusual behavior.
Channel 4	Cond Zone 1	Basket Tip		3.16	0.81	No unusual behavior.
Channel 5	Cond Zone 1	Guide Plate		3.14	0.80	No unusual behavior.
Channel 6	Cond Zone 2	Basket Tip		3.18	0.82	High average. High variability, at 7% > median.
Channel 7	Cond Zone 2	Guide Plate		3.07	0.77	Low variability, at 6% < median.
Channel 8	Cond Zone 2	Pipe Tip	Some minor pressure excursions observed.	3.02	0.76	Lowest average of scanivalves: 0.1 in-Hg < median.
Channel 9	Cond Zone 2	Basket Tip		3.05	0.77	Low variability, at 5% < median.
Channel 10	Cond Zone 3	Basket Tip		3.15	0.80	No unusual behavior.
Channel 11	Cond Zone 3	Guide Plate	Some minor pressure excursions observed.	3.05	0.77	Low variability, at 7% < median.
Channel 12	Cond Zone 3	Basket Tip	Some minor pressure excursions observed.	3.07	0.77	Low variability, at 5% < median.
Channel 13	Cond Zone 3	Basket Tip		3.18	0.82	High average. High variability, at 5% > median.
Channel 14	Cond Zone 3	Guide Plate	Some minor pressure excursions observed.	3.04	0.76	Low average. Lowest variability, at 9% < median.
Channel 15	Cond Zone 3	Basket Tip	Sensor broke 8/26- under repair until mid-Nov.	3.24	0.77	Highest average of scanivalves: 0.1 in-Hg > median.
Plant P_Shell 1a	EtaPro Col M	Basket Tip	Mounted 10' above zones 1-3. Mnr prssure excrsns.	2.76	0.78	Lowest average of all estimates- 0.4 in-Hg < median.
Plant P_CND 1A	EtaPro Col AU	Indepdnt Gauge	Facing steam flow- frequent major malfunctions.	3.18	0.91	Highest variability of all estimates, at 33% > median.
Plant P_hotwell	EtaPro Col O	Thermocouple	Hotwell temp convrtd to pressure w/steam tables.	3.42	0.82	Highest average of all estimates- 0.3 in-Hg > median.
Plant P_exhaust hood	EtaPro Col U	Thermocouple	Exh Hd temp convrtd to pressure w/steam tables.	3.15	0.82	Three erratic spikes of 7 to 11 in-Hga.

The data in Table 4-1 summarizes the 19 pressure estimates and their performance data over the 78-day study period. Detailed conclusions and recommendations follow.

Conclusions

The results described below are based on the condenser pressure measurements and plant data collected in 2013. This warmer weather period of time resulted in operating conditions with comparatively low average turbine exhaust steam velocities of 200 to 300 ft/sec (at the turbine-condenser expansion joint) along with relatively high quality steam (containing some moisture).

1. The most accurate and reliable placement of condenser static pressure taps is between 1 to 2 feet above the inlet end of the tube bundle. With summertime low turbine exhaust steam velocity operating conditions, the location of static pressure taps at the condenser plane is not too important.

2. The study so far has not identified any major difference in the accuracy or reliability of the three gauge types. The basket tips and guide plates are much more costly, more difficult to fabricate in a utility shop and present greater frontal area to the steam flow than the simple pipe tip (a 1/8th inch diameter hole drilled into the downstream side at the end of a small pipe).

3. Except for the confidence and prudent engineering practice that comes from confirmations, the installation of only one pressure type device may be necessary. In the

data received to date, the pressure variations are slight and averages of two or more measurements are not needed.

4. At the host site, the plant measured turbine exhaust steam pressure via a basket tip, located about 12 feet above the tube bundle. The instrument is indicating 0.4 in Hg below the other measured condenser pressures. This important gage of plant and turbine performance may be inaccurate and it is recommended its source of error be determined and corrected.
5. At the host site, the turbine exhaust and hotwell temperatures were found to be very different when compared to the installed condenser test static pressure taps. Further analysis will determine if these indications are inaccurate and unreliable.
6. An independent pressure device recently installed was found to provide an unreliable and inaccurate measurement of the condenser pressure compared to the basket tips, guide plate, or pipe tap designs.
7. Pressure and pressure variability differences between device types and between zones were small, averaging about 0.04 in Hg and 0.01 in Hg, respectively.
8. Consistency of readings between the different device types (measured as the average of the look-across ranges of each type of device for each point in time) showed no clear difference between the devices (the largest difference between the 3 groups was about 10%).

It is emphasized that the above major conclusions are for condensers operating at relatively low steam velocities with high thermodynamic quality steam and therefore are tentative. During the remaining test program, the study will have the opportunity to examine the reaction, reliability, and accuracy of these popular condenser static pressure tap devices in periods of higher exhaust steam velocities, expected during the cooler ambient temperatures experienced during winter months. The dynamic effects of the exhaust steam velocities are more likely to have an influence on the condenser pressure measurements under those conditions.

Recommendations and Future Actions

The following areas should be addressed as the project continues:

- The Independent Sensor failed to provide variable pressure data for 38% of the 5600 readings, and even when it was appearing to work properly it had the highest variability of all the nineteen pressure estimates. If the root cause of its problem cannot be found and fixed, it will be considered unreliable.
- Pressure estimates from two of the four plant-based data sources tend to fall outside the measured values of the 15 Scanivalve data devices (P_hotwell temp is much higher than the 14 working Scanivalve channels and Pshell 1A is significantly lower than the 14 Scanivalve channels). It must be considered whether they truly reflect the pressure of the condenser. If these plant readings are an indication of some error, that error should be investigated by Ottumwa personnel.

- Consistency of readings between the different zones (measured as the average of the look-across ranges of each zone for each point in time) showed Zone 1 to have lower variability than Zones 2 and 3. This has been consistently noted in each observation period. The improvement in look-across range for Zone 1 compared to Zones 2 and 3 averages 63%. Calibration, mounting, steam flow profile, or other differences between Zone 1 and Zones 2 and 3 need to be investigated to determine if this difference is truly due to simple location or some other factor.

- The possible trends and spikes identified in the Trend Analysis section of this report should be investigated for cause.

5
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