RheoVac®

Instrument User's Guide

Your Condenser Performance Partner

RheoVac Instrument User's Guide

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0 Foreword

0.1 Problem Identification

It should be understood that all condensers have the potential to operate at or below an achievable pressure, P_A, determined by first principles that take into account condenser material properties and classical mathematics. It should also be understood that all condensers have the potential to operate with condensate dissolved oxygen (DO) << 10 ppb for air in-leakage (AIL) maintained below condenser venting equipment capacity. Unfortunately, only a limited number of condensers operate at the low value of P_A and below 10 ppb DO. In fact, many older condensers, as well as a number of newer condensers, operate chronically in excess of 0.5"Hg above the achievable pressure value and greater than 15 ppb DO.

This fact may not be visible to many condenser operators because the "design" condenser pressure is often confused with the "achievable" pressure P_A. By way of example, it is not commonly understood why, and accepted that, condensers are "over designed," since a cleanliness factor of about 85% is employed in design for clean tubes, using a "practical" heat transfer coefficient (U) as provided by the HEI standard [1]. Further, there are many experience-driven observations that have led to "rules of thumb" as shown in Table 1 for operating and maintaining condensers.

Table 1: Commonly Used "Rules of Thumb"

Rule for Air In-leakage: 1SCFM/100MW
Guideline for Circulating Water ΔT: Stratification exists – average values are used for performance computations
Rule for Hotwell Condensate Subcooling: Subcooling exists – subcooling is expected and a consequence of condensation
Oxygen Content of Condensate: High DO is related to high air in-leakage HEI: DO is a function of venting equipment capacities being 2 to 6.7 greater than AIL Oxygen Treatment (OT) programs have relaxed targets for condenser condensate dissolved gases
Condenser Design "Cleanliness Factor" (CF): U reduction factor: HEI requires the design CF to be "selected by the Purchaser"

These non-science and non-engineering based conclusions and observations, that change periodically, have been developed by condenser manufacturers and by other organizations. They have been incorporated into Guidelines and have been used by managers, engineers, operators and experts in the power industry for decades. The basis for condenser performance description is, however, a proven age old knowledge of cross or counter flow of two fluids in heat exchangers. This generally applies to two fluids where one fluid is cooled and the other heated and are classed as liquid-liquid, liquid-gas, or gas-gas heat exchangers. The governing equation for the process is given by the Fourier equation:

$$Q = U\ A\ \Delta T_{lm}$$

Where Q is the amount of heat transferred, U is the heat transfer coefficient, A is the heat exchanger surface area and ΔT_{lm} is the logarithmic mean temperature difference between the two fluids. The equation works for all types of heat exchangers and has been proven using first principal analysis, which agrees quite well with experiment, to within expected error.

For condensers where one fluid, steam, is condensed at its saturation temperature and therefore has no temperature change, up or down, for the most part, the equation holds until noncondensable gases are introduced with the steam. This is where all analysis fails and attempts to solve this problem has been the subject of investigation since before the use of computers and continues today using such programs as finite element analysis and computational fluid dynamics. Despite these efforts, none have resulted in sufficient comprehension suitable for optimizing the design of condensers nor to providing a reliable means to modify condensers exhibiting very poor performance.

Appropriate comprehension and adequate measurement are needed to resolve these issues. The understanding of all causes for excess condenser pressure and all mechanisms responsible for DO in condensate is needed to properly diagnose behavior of this important balance of plant component.

0.2 Proper Monitoring

In the field of management, it is said "you can't control what you can't measure." This saying holds somewhat true in engineering. If one wants to diagnose a complex system one needs to know all of the system inputs and outputs, and the condenser is certainly a complex system. Figure 1 shows all of the significant inputs and outputs of a steam surface condenser. Vent line gas flow and circulating water flow are highlighted in the illustration because instruments for the direct measurement of these parameters have historically been unavailable or inadequate for comprehensive performance and continuous monitoring.

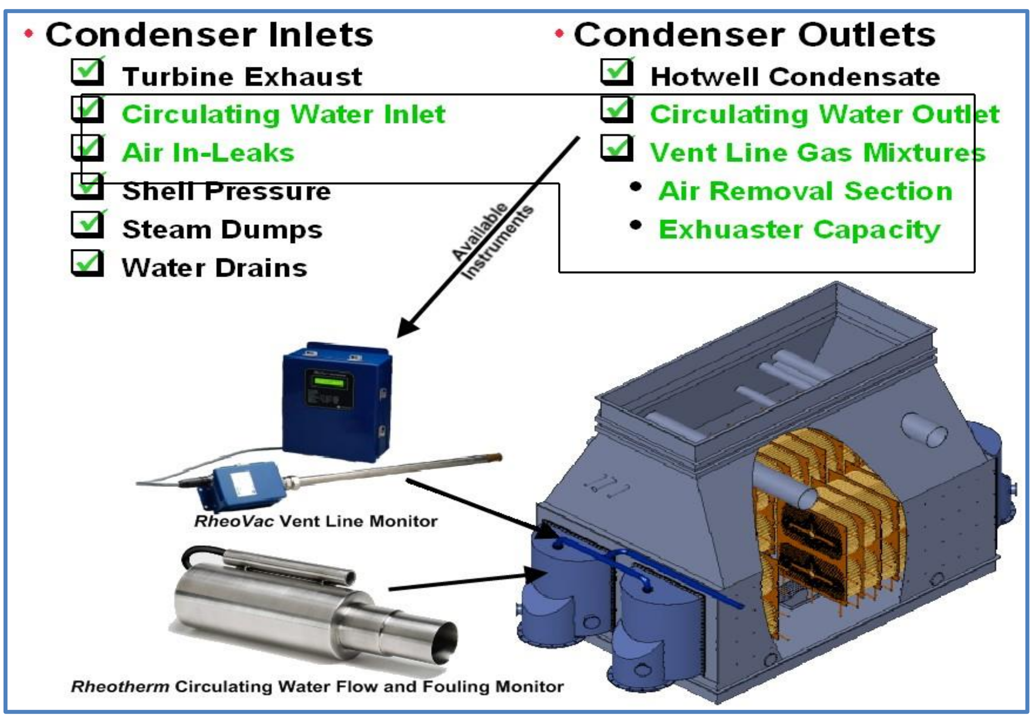

Figure 1: Illustration of Condenser Inputs and Outputs

In 1994 the *RheoVac*® Multi Sensor Probe (MSP) [2] measurement technology was invented and an instrument was made commercially available. This instrument provides four primary measurements and six computed measurements used in performance diagnosis. Since its introduction significant advancements have been made to the fundamental understanding of the dynamic nature of the air water vapor mixture with steam surface condensers.

More recently, the *Rheotherm*® Circulating Water Flow and Fouling (CWFF) meters [3]has been introduced for direct measurement of single tube flow and outlet temperature allowing computation of total flow, macro and mico-fouling.

These continuous monitoring instruments are shown in the illustration of Figure 1. Direct measurement of circulating water velocity, tube fouling, tube sheet fouling, outlet thermal stratification, pump/exhauster capacity, and air in-leakage are essential for a comprehensive condenser monitoring program and are achievable using these instruments.

0.3 Excess Backpressure

Shown in Figure 2 is a unique graph and mathematical prescription that applies to all steam surface condensers regardless of operating condition. This graph and the relationships shown provide engineering basis for root cause analysis of excess pressure in a condenser. It is the intent of this section to provide guidance on interpreting these plots based on sound physical reasoning. These relationships have been substantiated by MSP and/or CWFF measurement in hundreds of different operating condensers. They also provide a basis for identifying root causes of poor performance, poor water chemistry and the establishment of air pockets that can exist in tube bundles referred to generally as air bound (AB) zones.

Figure 2 shows the general relationship between condenser pressure (P_C) and air in-leakage (AIL). Also provided in the Figure are the different components that contribute to overall excess condenser pressure, (P_{ex}), above the achievable condenser pressure (P_A). P_A can be approximated using components of the standard HEI condenser design calculations. The highlighted regions in Figure 2 are defined and described in Table 2.

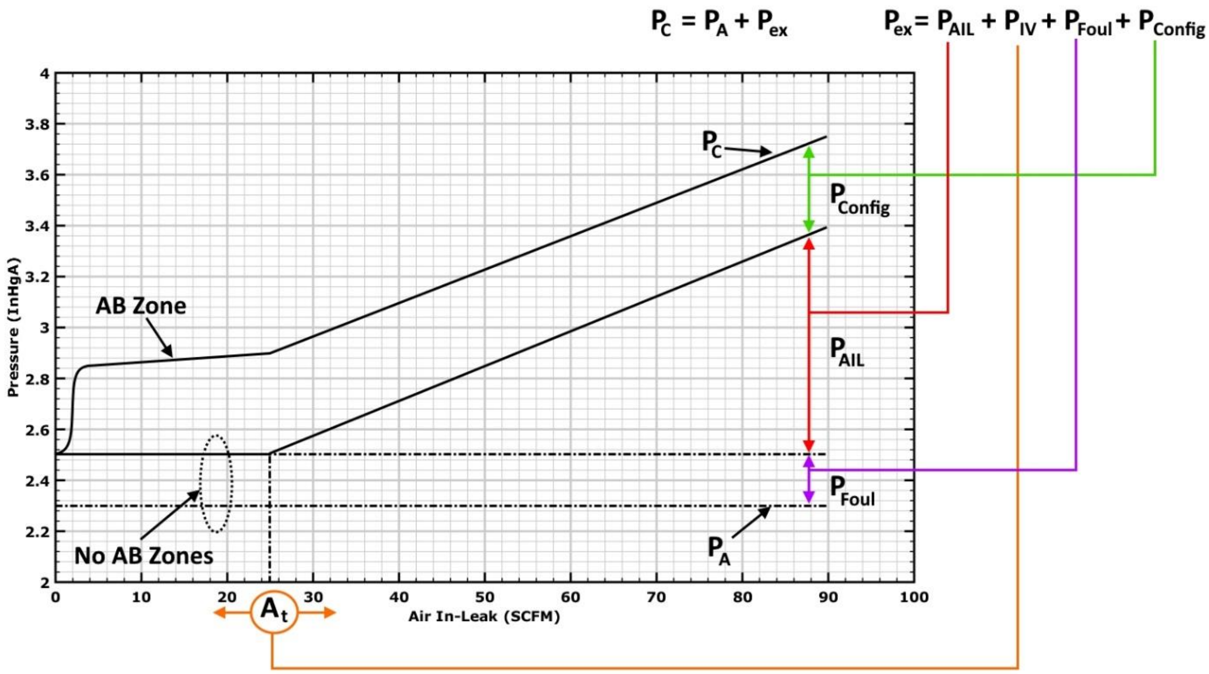

Figure 2: Condenser Pressure, P_C vs. AIL Relationship

There are four different primary root causes for correctable excess pressure, P_{ex}: air in-leakage, inadequate venting, fouling, and configuration-caused air binding. Much attention has been given to eliminate or mitigate the first three of these root causes. The excess pressure caused by air binding is significant, and exists for condensers with configuration deficiencies at very low levels of air in-leakage. Correcting this root cause of excess backpressure requires a well-designed and planned condenser retrofit or modification. Proper corrective action will have a large, long term, sustainable impact on performance and should be given proper attention.

Table 2: Definitions and Descriptions for Figure 2

P_{ex}	Excess Pressure – a summation of all contributors to excess condenser pressure.
A_t	A finite amount of air in-leakage identifying a threshold whereby a contribution to excess condenser pressure due to air ingress begins. P_A is the lowest pressure obtainable by the condenser for its required operating conditions with AIL # A_t.
P_{AIL}	Excess pressure due to AIL above a pressure onset threshold value A_t determined by the pump capacity. P_{AIL} is identified by excessively high AIL and the resulting formation of stagnant zone where air is stored causing P_{ex} to increase. Tests are available using a MSP instrument for air in-leakage; this monitor unambiguously determines if pump capacity is sufficient to mitigate excess backpressure caused by existing air in-leakage. Measured amount of air in-leakage, in SCFM, or total mass flow, in lbs/hr, can be compared to pump capacity curves at the measured suction pressure to determine adequacy of the exhauster system.
P_{IV}	Excess pressure due to insufficient venting; determines the value of AIL for A_t where pressure begins to rise. P_{IV} is identified by excessively low pump capacity. The measured water vapor to air mass ratio is an indicator of excess condenser pressure caused by relatively high air in-leakage or from degraded pump capacity. Empirical data shows that a water vapor-to-air mass ratio above 3 indicates no excess back pressure due to insufficient venting capacity.
P_{Foul}	Excess pressure due to fouling. P_{Foul} is identified by tube fouling measurements such as differential waterbox pressure or through newer technologies such as the circulating flow and fouling monitor based on *Rheotherm*® technology, patent pending. If neither one of these technologies is available, then P_{Foul} can also be determined by comparing high-resolution condenser data (including AIL data) with known good baseline data following tube cleaning. Also, P_{Foul} results in the lower curve being shifted upward.
P_{Config}	Excess pressure due to condenser design configuration causing air binding. P_{Config} can be identified by: high chronic DO (>5ppb), measured low cleanliness factors (clean tube measurements), steam and condensate cycle corrosion, hotwell subcooling, and condenser pressure dependence on AIL below the A_t value. It can be described by steam dynamics modeling using CCMT to establish boundary conditions.
No AB Zones	The curve containing the horizontal line at P_A is the achievable condenser pressure response to AIL if no air bound zones exist. Note that P_{ex} 0 for AIL < A_t.
AB Zones	The upper curve marked by "AB Zone" is representative of the condenser pressure response to AIL if air bound zones exist (typical condensers). Indicators of this response are contained within the P_{config} definition. Note that P_{ex} increases for all increasing values of AIL and over the entire range of AIL.

0.4 Understanding Air Storage

There are two means by which air can preferentially concentrate at locations within a tube bundle and result in a rise in condenser pressure. The first is operations-caused and occurs when air in-leakage exceeds the air removal equipment design capacity at the existing suction pressure. This operations-caused air storage can be a result of increased air in-leakage or decreased exhauster capacity. The mechanism that causes the pressure to rise in both cases is the establishment of an air storage region around the entrance to the air removal section (ARS) of the tube bundle. This kind of storage region has been called a stagnant (S) zone [4], Figure 3. Within this region, condensation is reduced because of the presence of air and the temperature is lowered, causing low water vapor pressure and high air partial pressure. Condensate falling through this region is lowered in temperature, promoting the dissolution of entrapped gases within the storage region. This mechanism transports the dissolved gases into the hotwell condensate.

The second storage mechanism is an air bound (AB) zone that is located away from the ARS and exists as a result of the tube bundle configuration, seen in Figure 4. Air bound zones develop as a result of steam flow in a bundle that does not provide a means for air removal. This is common in tube bundles having multiple bundle subsections.

These air storage zones are more difficult to identify without proper measurements. They are regions of low condensation that give rise to higher condenser pressure and high dissolved gases in hotwell condensate. They lead to high condenser pressure, DO and cation conductivity generally above the condenser performance values provided by the manufacturer. Air bound zones are inherent to the condenser design; therefore, even small AIL will promote their existence.

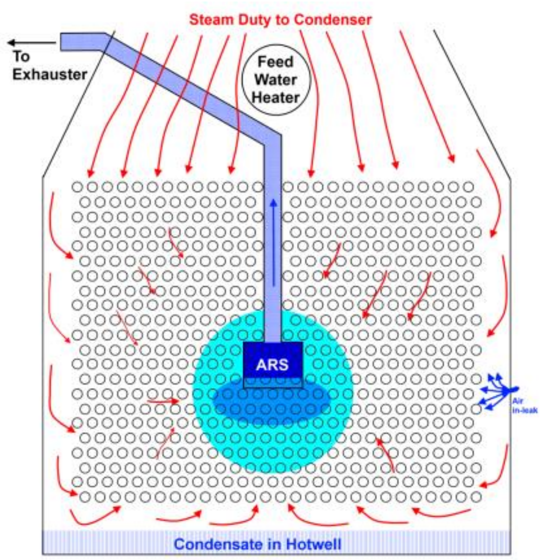

Figure 3: Stagnant Zone

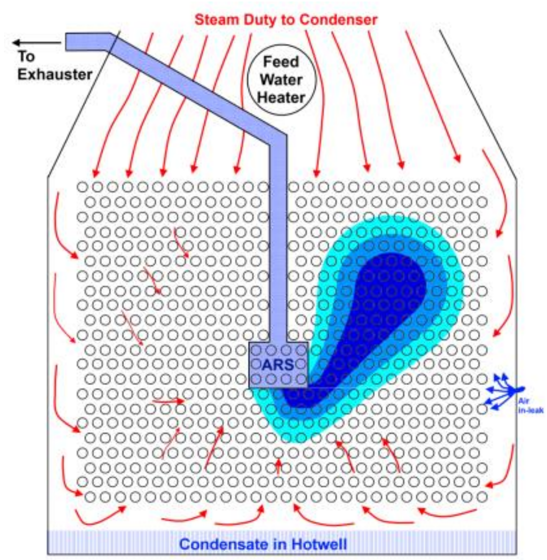

Figure 4: Air Bound Zone

1 About this User's Guide

1.1 Introduction

This guide is intended to provide plant engineers and chemists with an understanding of how the *RheoVac*® instrument can be utilized for more than just monitoring air in-leakage flow rates[1]. It will provide the user with a method for evaluating abnormal operating conditions and improving plant performance. The methodology involves 1) understanding important instrument outputs, 2) validating data, 3) establishing baseline data and alarm limits and 4) interpreting data to determine appropriate action. It is expected that, after reviewing this guide, a *RheoVac* user will be able to analyze problems associated with the condenser and the vacuum system operations, reduce time to diagnose problems, and quantify plant efficiency improvements.

Periodic manual readings using a variable area type flow meter, such as a rotameter, located downstream of the air removal equipment have long been the accepted method for monitoring air in-leakage (AIL) to the condenser. This method of monitoring flow at the vacuum equipment discharge has a number of inherent limitations including non-continuous readings preventing event time recording, manual data recording, the inability to differentiate between air in-leakage at the exhauster equipment versus in-leakage to the condenser, the inability to monitor the vacuum equipment capacity, and the inability to correlate an air in-leakage value to condenser performance. The *RheoVac* instrument was originally developed to overcome these limitations. Some of the many uses and benefits are listed in Section 1.2.

A *RheoVac* instrument is an investment for performance enhancement and cost reduction. According to an early EPRI study and later independently verified by others, excess turbine back pressure of 0.3" HgA will cost a 400 MW plant $375,000 per year in additional fuel [5]. This same 0.3" HgA excess back pressure represents an increase in plant heat rate of about 48 BTU/kW·hr or a 0.53% loss of load for base loaded plants. Slight elevation in excess back pressure occurs gradually and is typically not noticeable using standard instruments, but can be identified and quantified by users of *RheoVac* instruments and Bionetics' analysis techniques.

1.2 Uses & Benefits

The *RheoVac* instrument has many uses and benefits, some of which are:

- Provides continuous air in-leak monitoring as recommended by EPRI
- Provides measurement of vacuum equipment capacity and suction pressure, which allows for continuous monitoring of vacuum equipment performance
- Provides measurement of Water-to-Air Mass Ratio (W/A), which is directly correlated to air storage in the condenser, section 2.2 discusses the importance of this parameter; W/A ratio can be plotted vs. Cleanliness Factor to quantify the performance losses due to air storage in the condenser[2], see Figure 6.
- Provides continuous data logging; provides high resolution, wide range and accurate data
- Can be configured to be a standalone comprehensive condenser performance monitor by adding inputs for cooling water temperature, cooling water flow and steam pressure/temperature instruments to the *RheoVac* central computer.

[1] This guide is not intended to replace the installation and operation manual.

[2] Bionetics recommends that the W/A ratio be monitored regularly and be given a higher priority than air in-leakage flow rate when determining if condenser performance is degraded as the W/A ratio is directly correlated to the condenser performance.

2 Understanding Instrument Outputs

2.1 Measured and Calculated Parameters

The primary functions of the *RheoVac* instrument are to provide an accurate indication of the amount of noncondensables[3] (frequently just air) and the total flow (water vapor and noncondensables) that is being extracted from the condenser. These measurements provide visibility into the performance of the condenser and exhauster system. Your *RheoVac* monitor makes four primary measurements shown below in Table 3 and Figure 5: RheoVac Multi Sensor Probe. These measured data are used to provide the output parameters listed in Table 4.

Table 3: Primary Measurements

Parameter	English Units	Process Variable Definition
Pressure	In. HgA	Measured absolute pressure at the *RheoVac* probe head. A highly accurate pressure measurement. Generally will be 0.1 to 0.5"HgA below an independently measured condenser pressure.
Temperature	°F	Measured temperature of the flow media.
Relative Saturation	%RS	A direct measurement indicating the departure from saturation of the air/water vapor mixture being removed from the condenser vent line.
Total Mass Flow	lbs/hr	The measured total mass flow rate of the mixture of air/water vapor mixture. It is representative of the capacity at the operating suction pressure of a constant mass flow device such as a steam jet air ejector (SJAE).

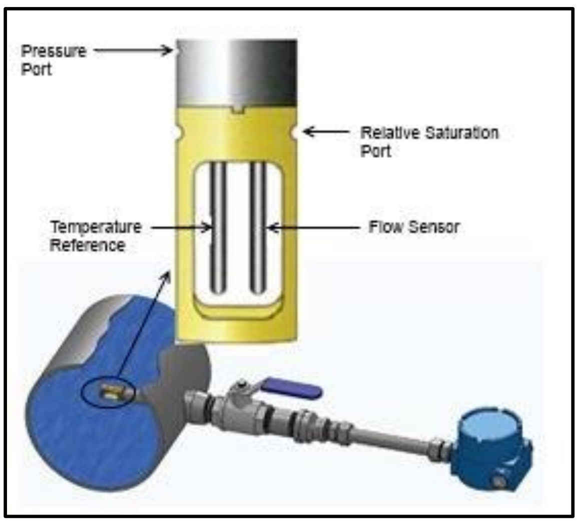

Figure 5: RheoVac Multi Sensor Probe

[3] The term "noncondensables" more accurately describes the gases that affect condenser performance, this term is more prevalent in BWR generating facilities whereby the noncondensable gases contain a large amount of H_2 gas.

Table 4: Calculated Parameters

Parameter	English Units	Process Variable Definition
Air In-Leakage	SCFM	The air flow rate in the vent line, normalized to standard conditions (70°F, 29.92" HgA).
Actual Volumetric Flow rate	ACFM	The volumetric flow rate of the gas mixture leaving the condenser. It is representative of the capacity at the operating suction pressure and temperature of a constant volume device, such as liquid ring vacuum pumps (LRVP).
Water-to-air Mass Ratio*($^W/_A$)	lbs/lbs	The ratio of water vapor flow rate to dry air flow rate. *Defines "vacuum quality" (see Section 2.2).
Water Vapor Mass Flow	lbs/hr	The water vapor component of the gas mixture being removed from the condenser.

2.2 The Most Important Output – Water to Air Mass Ratio (W/A)

Conventional wisdom held that air in-leakage should be kept as low as possible. This believe is still held by some. An old commonly used industry rule of thumb was 1 SCFM per 100 MW of power generation. This rule originated from Westinghouse but did not account for sizing of original equipment or efficiency in bundle design to guide and remove noncondensables [6], [7]. However, conditions vary greatly from one condenser unit to another and these guidelines may be misleading in many cases, resulting in excessive resources being committed to reducing air in-leakage that, if reduced, would not result in improvements of any value.

Bionetics' research, based on data gathered following the introduction of the *RheoVac* technology, has led to a new perspective that Air In- Leakage (AIL) is not a significantly recognizable problem unless many tubes in the condenser become air bound and the effective condensing surface area is decreased. This condition occurs when air in-leakage exceeds the air removal equipment's capacity to extract it under the given operating conditions, primarily condenser pressure. The water-to-air mass ratio (W/A), an output of the *RheoVac* instrument, can be used to determine when air in-leakage exceeds exhauster capacity. A threshold point can be found (typically around W/A=3) that identifies the onset of excess condenser pressure due to the forming of stored air around the air removal section; that is, the formation of a stagnant zone as described in the Forward of this guide. Therefore, **Bionetics recommends using the water-to-air mass ratio as the primary parameter for monitoring the condenser**. The water-to-air mass ratio is a calculated value of the ratio of water vapor density to air density of the gas mixture in the air removal vacuum line. Equivalently, it is also the ratio of the water vapor to air mass flow rates.

The value of the water-to-air mass ratio has significance in determining the vacuum system adequacy for a given operating condition. The water-to-air mass ratio depends not only on the amount of air in-leakage being removed but also on the existing exhauster capacity. The capacity can be a function of the number and type of exhauster used, operating conditions (environmental or motive), suction side pressure (condenser pressure), discharge pressure (generally atmospheric), and mechanical condition (wear) of the exhauster(s). It is important to understand that for a given amount of air in leakage an increase in exhauster capacity—for example, turning on an additional vacuum pump—will result in an increase in the amount of water vapor flow; therefore, an increase in water-to-air mass ratio.

As a general rule, a water-to-air mass ratio greater than 3 should be sought to minimize turbine back pressure due to the amount of air in-leakage with regard to exhauster capacity. Based on this observation of mass ratio measurement as related to correctable pressure, Bionetics has defined a desirable "Vacuum Quality" as being a pressure value where the water to air mass ratio is above 3 as a general case for most condensers. The value for a specific condenser system can be determined by performing a very simple but informative air in-leakage test as described in Section 4.1.

It has been shown through testing and observance of plant data that as air in-leak is reduced, the total pressure decreases until the W/A reaches a value of approximately 3. After reaching this value, the pressure remains relatively constant as further reduction of air in-leak is made. However, as the pressure remains relatively constant with declining air in-leak, the mass ratio continues to increase. It could then be concluded that if the mass ratio is significantly higher than 3 and more than one exhauster is running, an exhauster can be taken offline until the minimum number remains "on" to keep the mass ratio above 3. Equivalently, if a new leak occurs causing the mass ratio to fall below 3, an additional exhauster should be activated.

It should be mentioned again that a mass ratio of 3 is just a rule of thumb and this mass ratio threshold value is condenser design dependent. Bionetics recommends performing air in-leak testing to develop a curve for each unit like the one shown in Figure 6: Relationship between water-to-air mass ratio and HEI performance factor. to determine the threshold mass ratio for a specific unit. If the testing cannot or has not been completed, then the mass ratio value of 3 should be used until such testing can be performed. Bionetics is available to provide on-site testing and data analysis to produce results similar to those below. A description of this testing is discussed in Section 5.1.

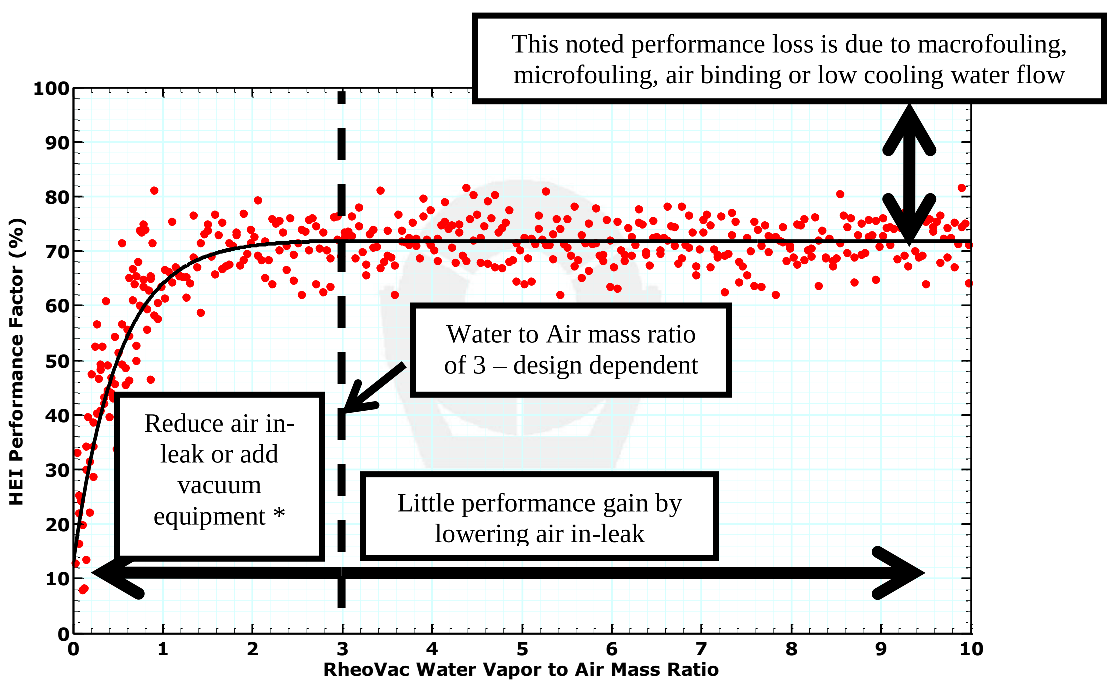

Figure 6: Relationship between water-to-air mass ratio and HEI performance factor.

*In this region of the graph a stagnant zone is being increasingly formed within the air removal section and expanding as the water to air mass ratio approaches zero within the main tube bundle.

This is due to low exhauster capacity or an increased amount of air in-leakage. Extremely small in-leakage will support a relatively fixed amount of air binding at water to air mass ratio values above 3.

3 Validating Primary Measurements

Maintaining confidence in the output parameters produced by the *RheoVac* instrument requires understanding the four primary sensors and being able to verify that they are functioning properly. The validity of the four primary sensors is easy to determine using common plant data.

The following is the recommended method for verifying the data to determine if the instrument is providing the accurate measurements expected. The goal of this procedure is to determine that pressure, temperature, total mass flow and RS sensors, which yield the *RheoVac* monitor's four primary measurements, are responding in expected manners to process conditions.

1) Compare *RheoVac* pressure, P_{RV}, to condenser pressure, P_{cond}. Experience has shown that the P_{RV} is less than 0.6" Hg and typically 0.4 "Hg lower than P_{cond}. This indicates that the *RheoVac* pressure sensor is reasonably accurate. Any deviation from this range, or noted sudden inexplicable changes in pressure reading, could indicate a failed or drifting pressure sensor in the multi-sensor probe when compared with the plant condenser pressure gauge.
2) Compare *RheoVac* temperature (in the vent line), T_{RV}, to the hotwell temperature and circulating water inlet temperature. The vent line temperature should be between the hotwell temperature and the condenser circulating water inlet temperature. If temperature exceeds 160°F then refer to Appendix A, Steam Jet Blow Back.
3) The total mass flow, $\dot{m}_{t,}$ should be in the expected range for the exhauster(s) being used on your condenser. Check your exhauster's capacity curve in mass flow for a steam jet and in ACFM for a liquid ring pump. Total mass flow typically will be below 600 lb/hr per exhauster. Liquid ring pumps typically have a volumetric flow rate around 1000 to 2000 ACFM. Extremely high values (1000+ lb/hr) can indicate water carry over or wetness on the mass flow tips of the Multi-Sensor Probe – refer to Appendix B, Presence of Liquid Water in the Vent Line.
4) The *RheoVac* probe relative saturation measurement, RS, should be between 70% and 100% and should vary over time. Some systems run at 100% constantly and dip down below this value only occasionally. A few systems have been seen to run as low as 50%.

Check your *RheoVac* primary readings:

Pressure, P_{RV} : Probe pressure should be 0.1" to 0.5"HgA lower than condenser pressure

$P_{RV} < P_{Cond}$ (0.1 to 0.5"HgA typical, ~1" HgA under high AIL)

Temperature, T_{RV}: Probe temperature may be as high as hotwell temperature or as low as circ water inlet temperature; typically a few degrees below circ water outlet temperature and hotwell temperature

$T_{cw,in} \leq T_{RV} \leq T_{HW}$

$T_{cw,out} \pm 4°F \leq T_{RV} \leq T_{HW}$

Total Mass Flow, $\dot{m}_T$

$\dot{m}_T \leq$ 1,000 lb/hr (for large exhauster)

225 lbs/hr $\leq \dot{m}_T \leq$ 600 lbs/hr (per exhauster, typical)

if $\dot{m}_T >$ 1,000 lb/hr, check *RheoVac* internal deltaT; > 20°F

Relative Saturation, RS

RS < 100% and varying; typically 80 to 97%

Figure 7: *RheoVac* parameter typical range

4 Interpreting the Data

Using the *RheoVac* condenser monitoring system to understand your condenser's operating characteristics involves simultaneously evaluating several parameters provided by the *RheoVac* instrument along with other traditional condenser measurements. These parameters are best viewed using a multi-axis plot as shown in the case studies of the following section.

The diagnostic flow charts shown in Figure 8 and Figure 9 can be used to systematically evaluate the *RheoVac* data and narrow the search for the source of the excess back pressure. The process begins with evaluating water to air mass ratio. Recall that the measured mass ratio of 3 was noted previously to be the most important parameter, this identified use is why.

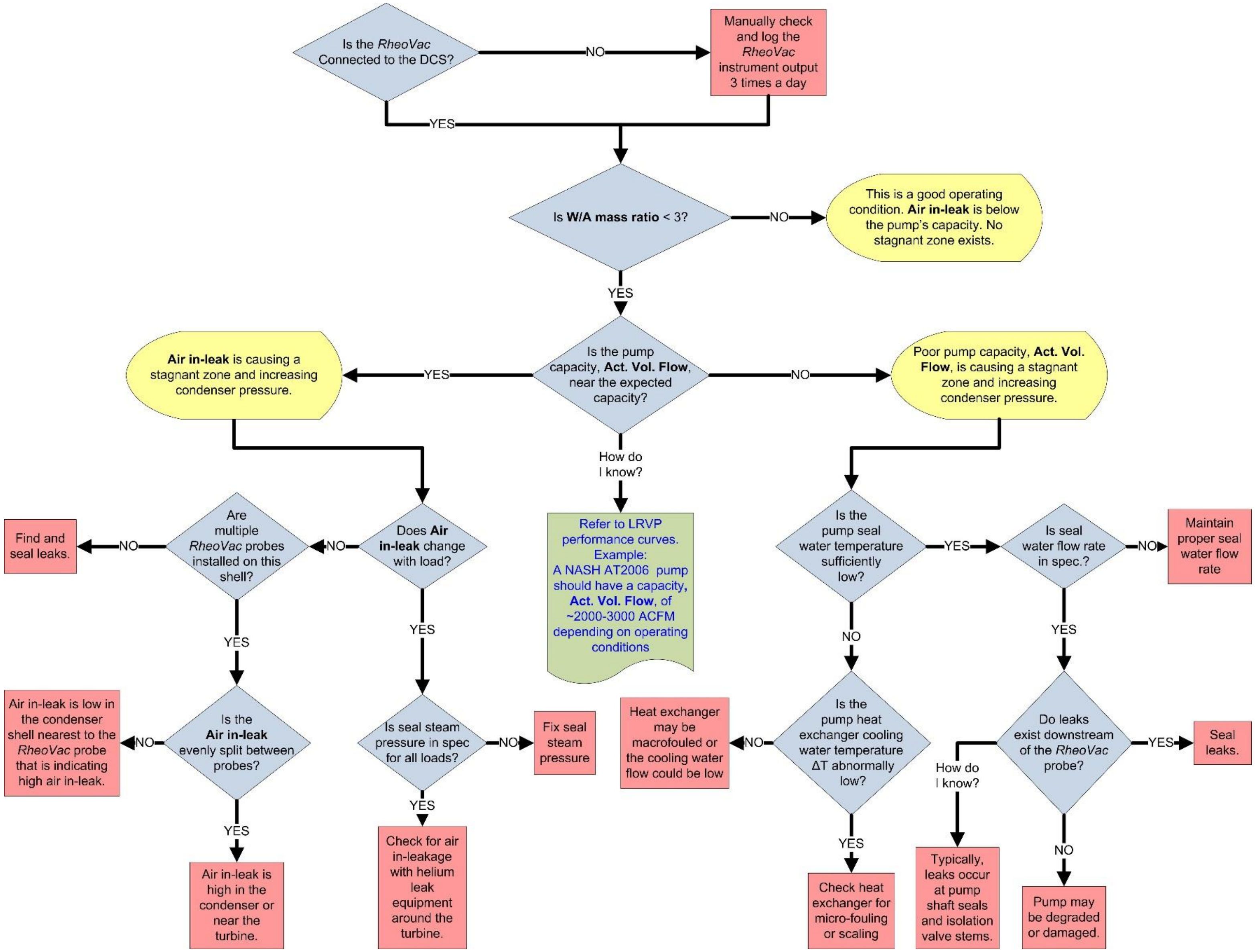

Figure 8: *RheoVac* Diagnostic Flow Chart© for units with Liquid Ring Vacuum Pump

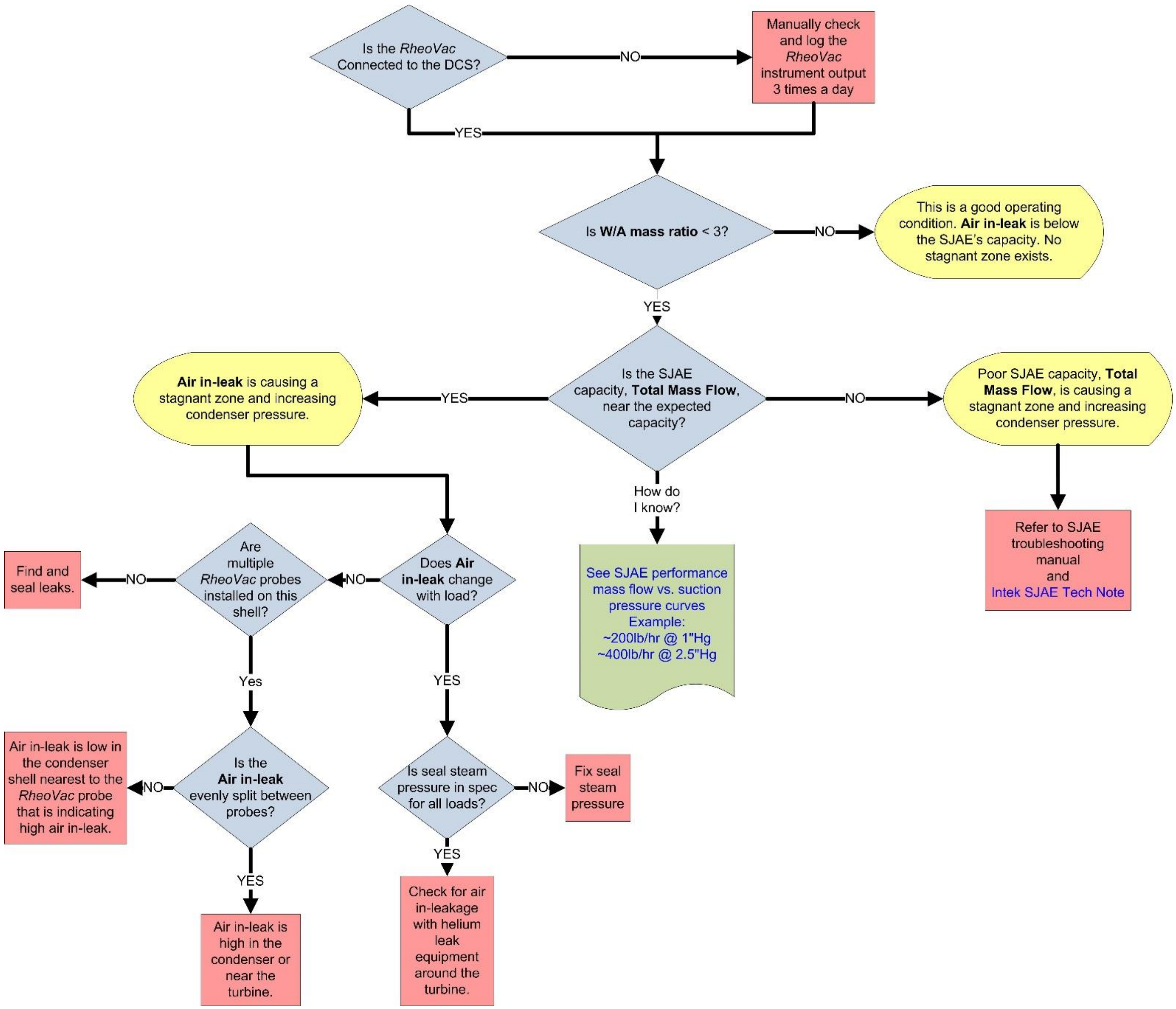

Figure 9: *RheoVac* Diagnostic Flow Chart© for units with Steam Jet Air Exhausters

5 System Characterization

Baseline testing is important to long term condenser monitoring. It defines the condenser's performance characteristics by creating a controlled change from normal to abnormal operating conditions and allows the response characteristics to be observed and recorded by the *RheoVac* instrument. These tests fall into two categories: air in-leak testing and exhauster performance testing. Without the *RheoVac* instrument, it is virtually impossible to tell which of these two conditions is causing a noted increase in condenser pressure. Without being able to differentiate between the two, valuable resources may be expended trying to find an air in-leak when the correct action should be addressing maintenance of the exhauster.

Prior to conducting tests as described below, a **"do not exceed condenser pressure" is determined by the plant operators** (typically ~5-8"HgA) to provide a safety margin below the turbine trip pressure. It is important to determine which pressure sensor is used as the turbine trip sensor and note any difference between this sensor and the performance monitoring sensor. Abort testing if this pressure limit is reached.

5.1 Air in-leak testing

Each condenser's response to air in-leak can vary greatly, even between condensers that are "identical" or built by the same manufacturer. Air in-leaks into the steam space will respond differently than air in-leaks at the exhauster or below the condensate water line. Leaks high in the condenser will be evenly distributed to all air off-takes; whereas leaks lower in the condenser will be scavenged mostly to the nearest tube bundle and its air removal section (a.k.a. air cooler section). The objective of testing is to create a chart of W/A mass ratio vs. HEI Performance Factor (refer to Figure 6).

Guidance for performing air in-leak tests is provided in EPRI 1014125 Air In-Leakage and Intrusion Prevention Guidelines, Section 3.2.1. Performing the air in-leak testing requires access to the condenser for a period of 4-8 hours. The unit load should be steady within ±2% for the duration of the test. Controlled air in-leaks should be introduced in various locations around the condenser; on all sides of the condenser and at different levels. The intent of this testing is to create an air in-leak profile and associated recorded response of the condenser dynamics that includes measurement of condensate chemistry, temperature, and condenser pressure. With the knowledge obtained from this testing, the time spent finding leaks can be reduced and will be a useful aid in future condenser operations.

A controlled air in-leak plumbed into the condenser though a rotameter is used to accentuate the effects of air binding and expand air storage in tube bundle designs prone to this common problem. A tradeoff of water vapor for air as the leak increases will result in a decrease in water to air mass ratio as water vapor is increasingly replaced by air in the total mass flow being removed by the exhauster. Increases in pressure and changes in W/A mass ratio are monitored closely to identify a capacity threshold at which a stagnant zone near the air removal section will be created. Once the exhauster capacity threshold is reached, condenser pressure will increase in its rate of rise with each additional step change in air that is introduced.

The test leak should be controlled using a gate valve. As a safety measure, a ball valve can be used in series with the gate valve for immediate stoppage if needed. The AIL is increased gradually in 5-10 SCFM increments up to a predetermined safe maximum level. Baseline air in-leakage is recorded when the test is started. The increased AIL levels should be maintained for at least 30 minutes to allow the condenser to reach an equilibrium point. Time permitting, 2-3 hours per air in-leak test location should be allotted. Results from an actual air in-leak test are shown as an example in Table 5.

Table 5: Timeline of AIL Testing

High Load Air In-Leak Test	AIL SCFM	Plant Pressure "HgA	*RheoVac* Pressure "HgA	Time
Target load established, baseline AIL level	59	1.4	1.26	9:20
Add 10 SCFM AIL to baseline	71	1.5	1.4	9:50
Add 20 SCFM AIL to baseline	82	1.7	1.55	10:20
Add 30 SCFM AIL to baseline	95	1.8	1.71	10:50
Add 40 SCFM AIL to baseline	107	2.0	1.85	11:20
Return to baseline AIL Level	59	1.4	1.26	11:50

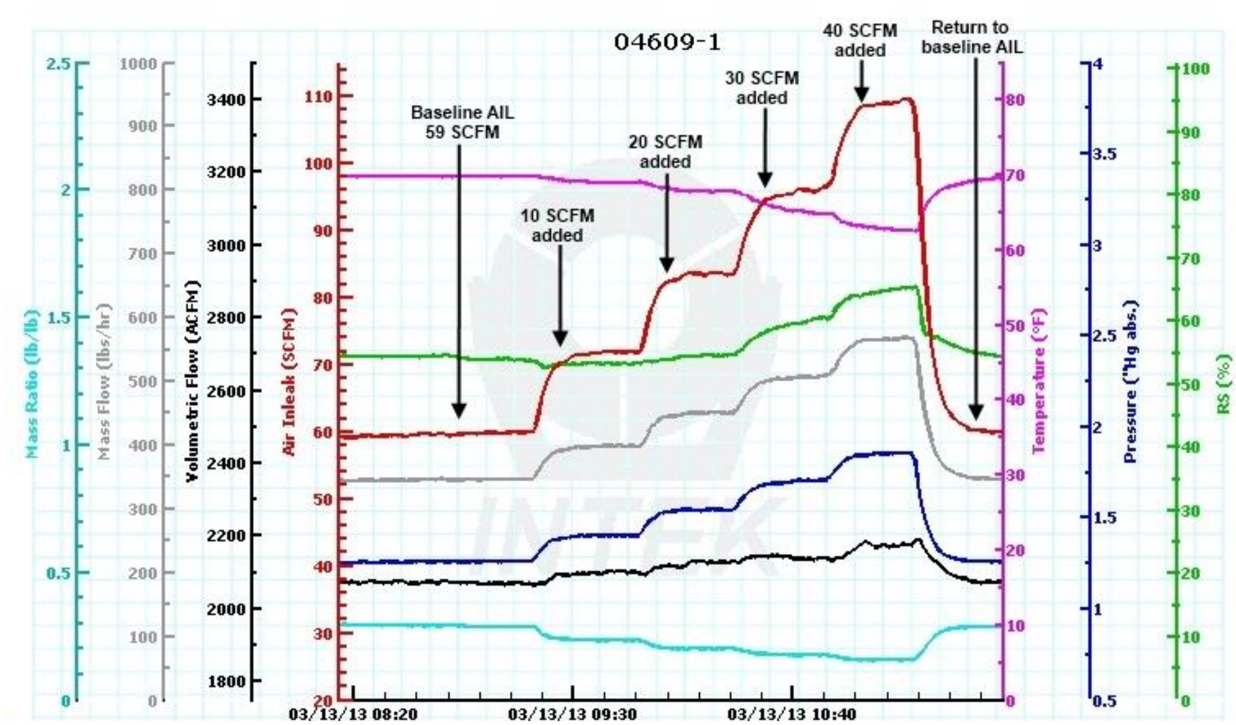

Figure 10: *RheoVac* Parameters during AIL Testing

The initial air in-leakage was already well above the capacity threshold of this system as noted by the W/A ratio being 0.3, significantly less than 3. Therefore, pressure increased with each 10 SCFM step of added air. Capacity measured by either total mass flow or actual volume flow also increased as the pressure increases. This data shows evidence of the system being controlled by the exhauster performance curve rather than by the condenser performance curve.

5.2 Exhauster System Performance Evaluation

Poor or reduced exhauster capacity will have the same detrimental effect as excessive air in-leakage; increased condenser pressure caused by air storage. This relationship highlights the importance of monitoring both air in-leakage and exhauster capacity. The *RheoVac* condenser monitor is the only instrument that can immediately differentiate between these two conditions by providing a direct measurement of exhauster capacity under operating conditions. In the absence of air storage, the condenser performance curve dictates the inlet pressure to the exhauster. As air storage occurs due to high air in-leak or low exhauster performance, the exhauster performance curve drives the condenser pressure higher.

A plot of exhauster capacity is obtained by evaluating *RheoVac* ACFM (or Total Mass Flow) vs. *RheoVac* pressure over time as shown in Figure 11. Shown here is the actual measured capacity of a steam jet ejector determined by the *RheoVac* instrument, along with the manufacturer's performance curve overlaid in black. The data points are colored based on a time scale to highlight trends over time that have a seasonal temperature dependency. Lower condenser pressure can be seen corresponding to winter operating months in the light blue and green data. The ejector capacity agrees closely with the design curve below a suction pressure of 2.5"HgA. Based on this trend, the SJAE is operating as designed. A possible cause for deviation from the design curve above 2.5" is elevated inter-condenser pressure as a result of higher condensate and cooling water temperature water passing through the SJAE inter/after condenser.

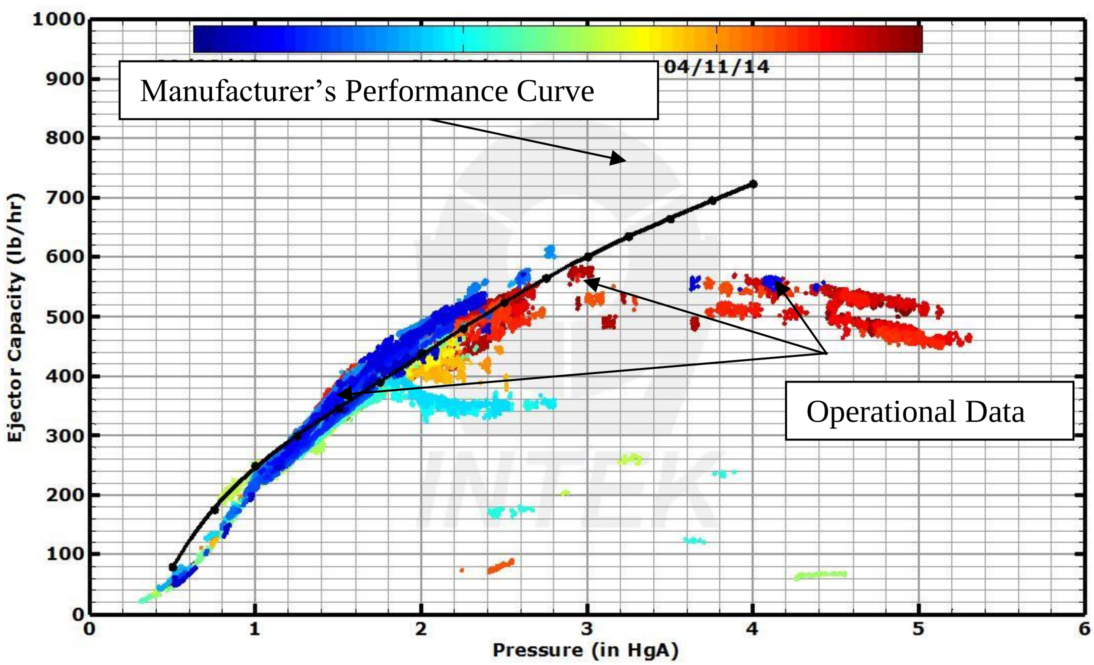

Figure 11: Exhauster Design Performance Curve vs. Operational Data

Exhauster capacity, in mass flow rate for SJAEs or volumetric flow rate for LRVPs is dependent on its inlet pressure. Thus, lower condenser pressure will result in low exhauster capacity. For this reason, air in-leakage may result in more air storage and lower condenser performance under cold circulating water conditions (or low load) when compared to warm circulating water conditions (or high load). For example, a 10 SCFM leak may not cause excess back pressure at 80º F inlet water temperature, but may do so at 70º F. In other words, the water to air mass ratio will decrease for a given air in-leak as condenser pressure decreases due to lower exhauster capacity during periods when circulating inlet water conditions are low.

A side by side pump capacity comparison can be performed to identify a poor performing exhauster. The pump capacity test outline shown in Table 6 is recommended for a condenser with 3 liquid ring vacuum pumps – A, B, & C.

Table 6: Pump Capacity Testing Outline

Pump Capacity Determination	Pressure	ACFM	Mass Flow	Duration	Elapsed Time
Target load established				-	0:00
30 minute hold				30 min	0:30
Pump A only					
30 minute hold				30 min	1:00
Pump B only					
30 minute hold				30 min	1:30
Pump C only					
30 minute hold				30 min	2:00
Return to normal operation					

The unit load should be steady within ±2% for the duration of the test; 2 hrs of steady load should be scheduled for testing.

Both pressure and pump capacity are monitored continuously to prevent exceeding the "do not exceed pressure". **Pump operation is altered and changes are maintained for at least 30 minutes to allow the system to reach an equilibrium point.** The *RheoVac* instrument's actual volume flow and pressure readings for each pump should be noted and compared to the manufacturer's performance curves to establish pump performance and evaluate if it is degraded.

6 Case Studies

6.1 Pump Capacity Comparison

The value provided by the ability to perform online evaluation of exhauster capacity cannot be overstated. Historically, plant operators have waited months for an outage opportunity that required specially assembled exhauster inlet structures, such as orifice trees to perform exhauster capacity testing. As shown, in this example (Figure 12), exhauster capacity is continuously monitored by the *RheoVac* instrument.

Summary of observations:

- **A 0.2"Hg difference in back pressure is seen between pumps**
- **Pump A shows much lower capacity than Pump B**
- **Distinct increase in both total mass flow and W/A mass ratio**
- **No change in air in-leakage**

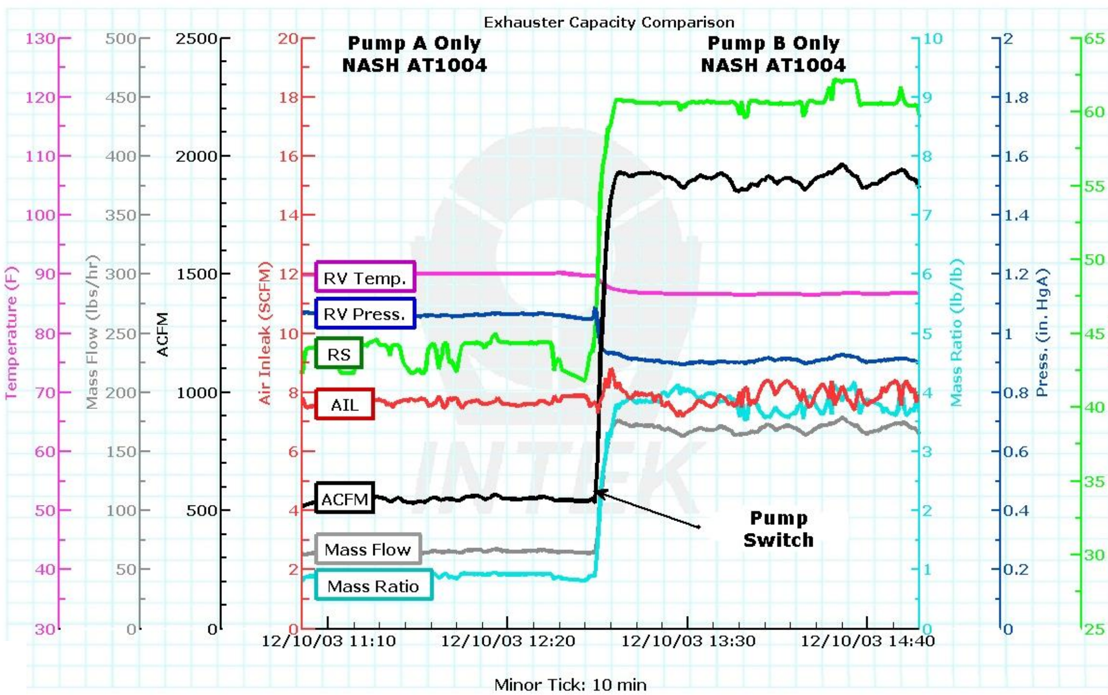

Figure 12: Pump Capacity Comparison, *RheoVac* data

Figure 12 shows *RheoVac* output parameters for a set of two Nash AT 1004 liquid ring vacuum pumps. Plant operators noticed a 0.2"Hg difference in back pressure between pumps and believed that one of their two Nash AT1004 exhausters is in need of maintenance. By performing a pump swap test and observing the *RheoVac* capacity parameters as evidence, operations can clearly show that one pump is underperforming. Pump A is pulling less than 1/3 of the volumetric flow (ACFM) that Pump B is removing from the condenser.

6.2 Trending *RheoVac* and Plant Data to Identify Leak Sources

The continuous data storage feature of the *RheoVac* instrument can be used to identify the onset of abnormal conditions. Returning to work after a weekend, plant personnel noticed that air in-leakage had increased significantly. By tracking the event back to its origin in time and cross referencing with plant data, the source of this event was quickly deduced.

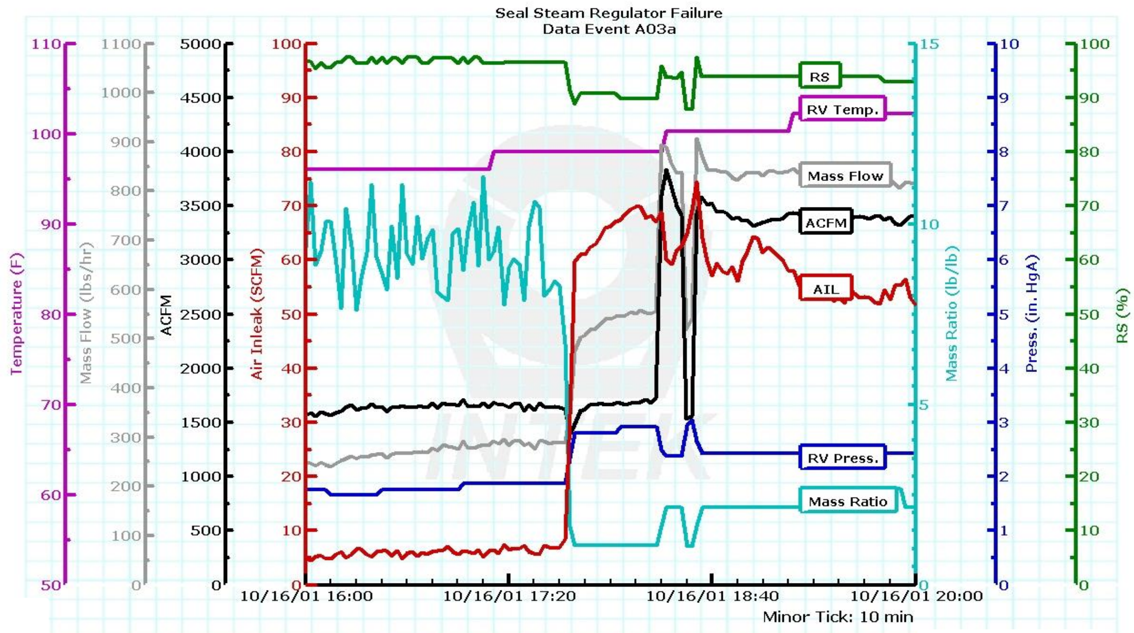

Figure 13: Data Trending Case Study, *RheoVac* Data

The air in-leak (AIL), shown by the red plot in Figure 13, had a baseline leak of ~5 SCFM. The plot shows a sudden increase in air in-leakage to ~60 SCFM at 17:42 on October 16th. Pressure increased when AIL increased with a corresponding decrease in mass ratio to below a value of 3, indicating that there is not sufficient exhauster capacity for the higher air in-leak flow rate. The operating pump capacity, shown by the black ACFM plot line, reflects that a second exhauster was turned on at 18:20 on October 16th in response to increased pressure. The additional pump capacity resulted in a slight reduction in pressure with a corresponding slight increase in mass ratio, but not to the previous levels. Use of *RheoVac* instrument data led to a search of their PI system for a corresponding event that occurred at the time of the noted AIL increase.

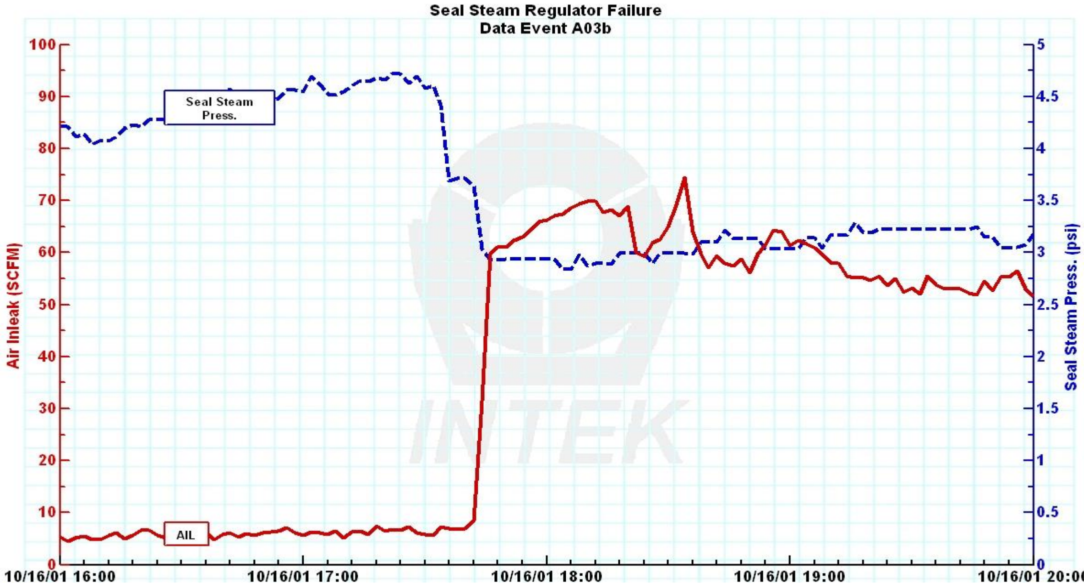

Figure 14: Data Trending Case Study, Plant Data

Figure 14 shows *RheoVac* measured AIL along with plant measured seal steam pressure data from the plant historian, and the cause for the AIL is identified as loss in seal steam pressure. Figure 15 shows that as the seal steam pressure (blue dashed curve) increases, AIL drops back down to a pre-upset level of 5 SCFM. This resulted in ½"HgA back pressure recovered as noted by the *RheoVac* probe and air in-leakage reduced from more than 60 to 5 SCFM.

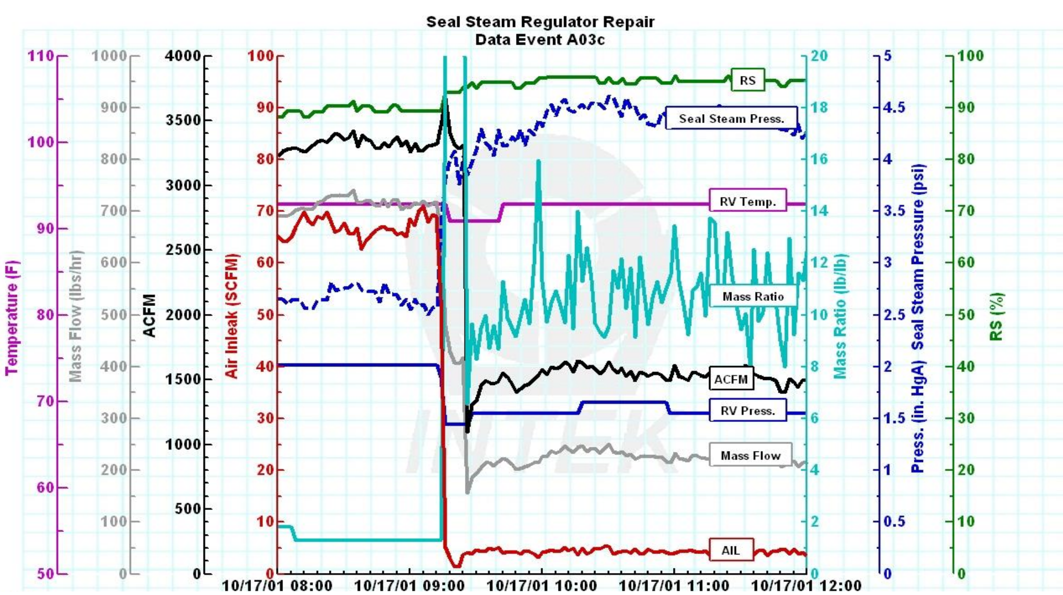

Figure 15: Data Trending Case Study, *RheoVac* and Plant Data

6.3 Validation and Locating Leaks with Multi-Probe Installations

A single *RheoVac* probe in the common condenser exhauster vent line allows the user to monitor overall condenser operation, including exhauster performance, but provides limited information helpful in locating the source of an air in-leak or to verify accuracy of all measurements in support of complete system analysis. When a leak is detected, a search of the entire vacuum system is required, which can take several days, and sometimes without success.

The *RheoVac* system is a scalable, multi-instrument device that can be configured to monitor any condenser arrangement. When multiple probes are installed such that each vent line plus the common line are monitored, measurement validation and leak locating is quickly determined and easily achieved.

Multiple probe installations can mitigate the time-consuming task of leak locating by identifying the region of the condenser where the leak can be found. Confirmation and validation of measurements can be achieved by swapping probes between locations to compare readings and by summing the source lines and comparing the value with direct measurement. A leak dispersed equally to all sections indicates the source is high in the condenser, such as the center joint seal, or at the turbine level, such as the gland seal steam system. A leak in the turbine seal sides parallel with the turbine shaft will enter the bundle below that side and is identified by greater measured air flow from that bundle.

In the example below, the user has a 2-probe *RheoVac* system with their -1 probe located on the A side of their condenser, and the -2 probe located on the B side. Notice that the -1 probe was seeing an air in-leak of 48 SCFM, while their -2 probe was seeing the typical 5 SCFM leak rate. Does the A side seem unbelievable when compared with the B-side? The two probes can be swapped to verify that both probes are reading accurately.

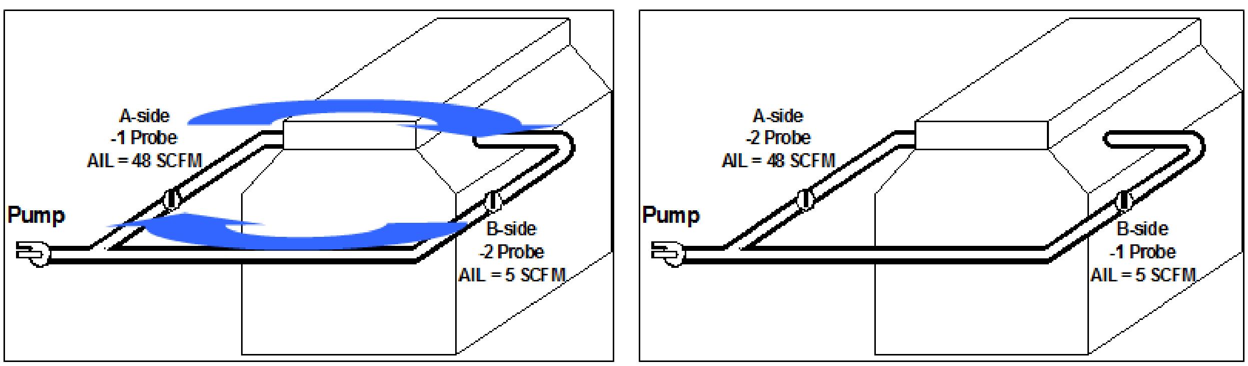

Figure 16: Probe Swap Case Study, Vent Line Layout

Probes can be swapped to verify readings, see Figure 17 and Figure 18 below for data curves. Air in-leakage will always travel to the closest ARS to be exhausted, so the leak was somewhere on the A side of their condenser. By using multiple probes, the *RheoVac* instrument has effectively cut the search time for this air in-leak in half.

When a leak is into one side of a single pressure, single shell condenser with two vent lines:

- **Air in-leakage is unbalanced, so not likely at turbine or center joint seal**
- **Air goes to closest air removal section so search can be focused on that side**
- **Pump capacity dominated by side with the leak forces air binding on non-leak side**
- **Probes can be swapped quickly and easily to verify readings**

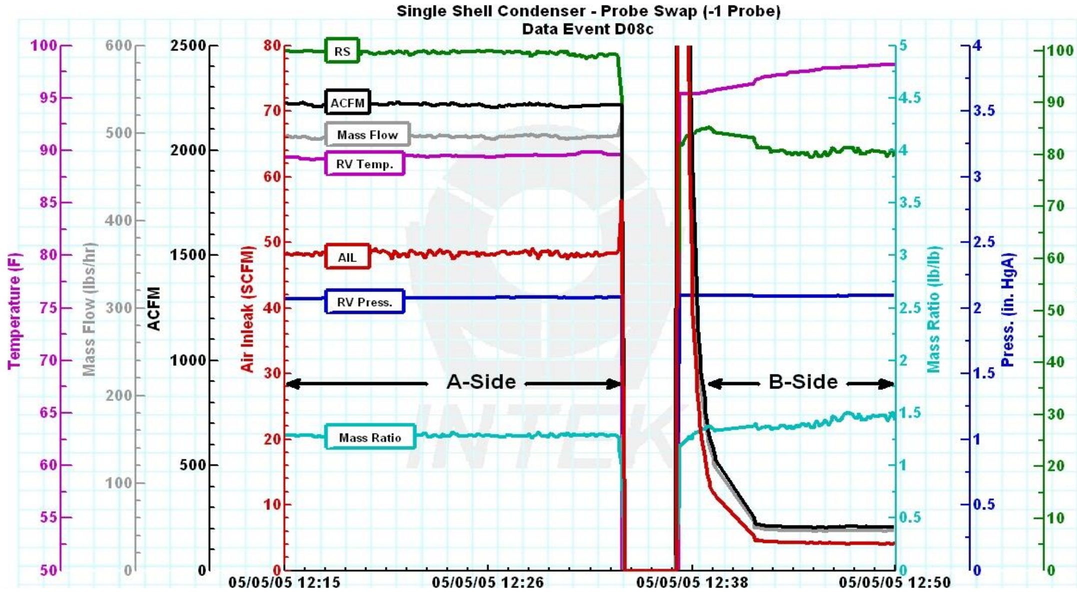

Figure 17: Probe Swap Case Study, -1 Probe Data

Figure 18: Probe Swap Case Study, -2 Probe Data

Appendices

A. Steam Jet Blow Back

If the SJAE motive steam pressure falls below the design conditions or conversely the discharge pressure is above the design conditions, then it can become unstable. When unstable, the pressure drop across the throat is reversed causing reverse flow; high temperature steam from the nozzle outlet is carried back through the vent line and into the condenser. Steam jet blow back following initial unit start up or during unit shutdown can be caused by several operating conditions. This can damage the SJAE nozzle, valves and instruments in the vent line, as well as components inside the condenser.

The RheoVac instrument data of Figure 19 shows proof of an unstable SJAE by recording the high temperature of the motive steam flowing toward the condenser. This event highlights the importance of maintaining proper motive steam control.

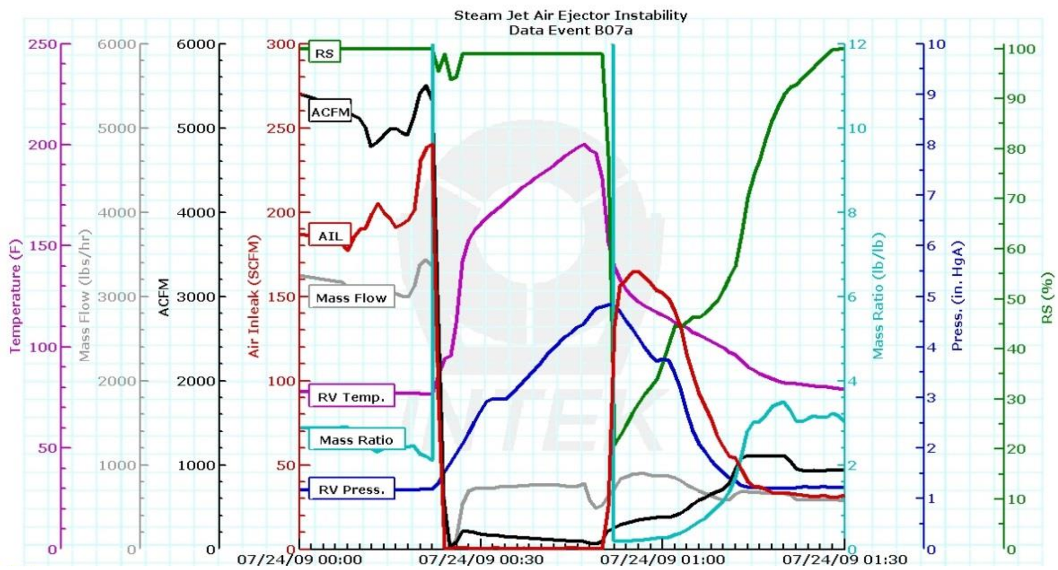

Figure 19: Steam Jet High Temperature Blow Back

- **Mass flow indication decreases**
- ***RheoVac* pressure and temperature ramp up**
- **RS sensor was overheated to 200°F (160°F max)**
- **Mass flow indicated steam blowback toward the condenser**
- **PI trend of steam pressure shows pressure drop during blowback**

B. Presence of Liquid Water in the Vent Line

Suspended liquid phase water (as a liquid mist) has been detected in the flowing noncondensable gas/water vapor mixtures found in condenser vent lines of some condensers. Identification of this inadvertent liquid was determined from evaluation of the output signal from *RheoVac* vent line monitors, also known as Multi-Sensor Probes (MSPs), designed for measurement of condenser air in-leakage, water vapor to air mass flow ratio and venting equipment working capacity. The accuracy of these important condenser performance related measurements are adversely affected by the presence of this entrained water. The identified intruder is also known to affect venting equipment capacity and cause an increase in the demand for condensate makeup water, both having a cost impact on the unit.

To remove the deleterious effects of liquid phase water on vent line flow measurements, without resorting to condenser modifications to remove the root cause, two low cost removal methods were devised. Because of the importance of the MSP measurement to power plant condenser performance monitoring and diagnostics, EPRI sponsored testing of these methods to evaluate their effectiveness. The results of this test program and the reasons behind the successful result were presented in a paper "Moisture Separation in Condenser Vent Lines" at the 2009 EPRI Condenser Technology Seminar and Conference in St. Petersburg, FL. The full project report is available in the EPRI Technical Report 1018345. [8]

Key project findings are:

- The MSP measurements are 100% protected when both the in-line and separator tips (MSTs) are implemented over the entire 8-month test period.
- The MSP measurements assisted in identifying and quantifying an out of calibration condenser pressure sensor.
- The MSP measurements show adequate venting even when the unit has a 100 SCFM air in-leak over the 8-month test period.
- The separated entrained water was measured up to ~1.5gpm, representing a loss to drain.

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[4] Electric Power Research Institute, "Air In-Leakage and Intrusion Prevention Guidelines," EPRI, Palo Alto, CA, 2008.

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[6] Westinghouse Turbine Division, "Air In-leakage Limits for Nuclear Turbines," *Operation and Maintenance Memo No. 029*, 12 March 1982.

[7] "TR-112819 Condenser In-Leakage Guideline," 2000.

[8] Electric Power Research Institute, "Condenser Monitor Moisture Separator Testing at Dynagy's Havana Station," EPRI, Palo Alto, CA and Dynegy Generation, Decatur, IL, 2008.