Introduction

Excess condenser pressure is costly. One of the most common losses in condenser performance is a result of air in-leakage. Air in-leakage is responsible for impeding heat transfer in the tube bundle which effectively reduces the condensing surface area and thus causes excess back pressure on the turbine. The excess back pressure reduces turbine efficiency and leads to reductions in plant generation and may contribute to condensate subcooling and increased levels of dissolved oxygen in condensate, dependent on condenser design.

The following case study shows how the *RheoVac* multi-sensor probe, (MSP) can assist Nuclear plants in identifying and quantifying air in-leaks in the condensers. The *RheoVac* MSP provides real time measurements of pressure, relative saturation, temperature, and mass flow in the air-offtake line. From these measured parameters air in leakage, volumetric flow rate, and the water to air mass ratio are calculated. Data provided by the *RheoVac* system before and after leaks are repaired provides the user with quantification of air in-leakage reduction as a result of maintenance efforts, data useful for narrowing the search areas for the air in-leak, and provides an independent continuously measured value that indicates if condenser pressure can be reduced if air in-leakage is further reduced (the water-to-air mass ratio value).

Unit description and background

A two-probe portable *RheoVac* system was sent to Nuclear station in the fourth quarter of 2019. The plant was experiencing higher than expected condenser air in-leakage and wanted to use the *RheoVac* system to help evaluate the conditions, quantify the air in-leakage, quantify the total flow in each off-take, and ultimately assist in leak location identification. The station has one Combustion Engineering two-loop pressurized water reactor (PWR) and produces 1240 MW of electricity since their last refueling. The 3-zone single pressure condenser has two vacuum lines per zone exiting through the shell above each inlet water box, with all six air-offtake lines tying into a common line, see Figure 1 below, leading to a bank of three Nash exhausters (CL 3005 x1, AT 3004 x2). Since a refueling outage 8 months earlier, the plant had been operating with both Nash AT 3004 exhausters running.

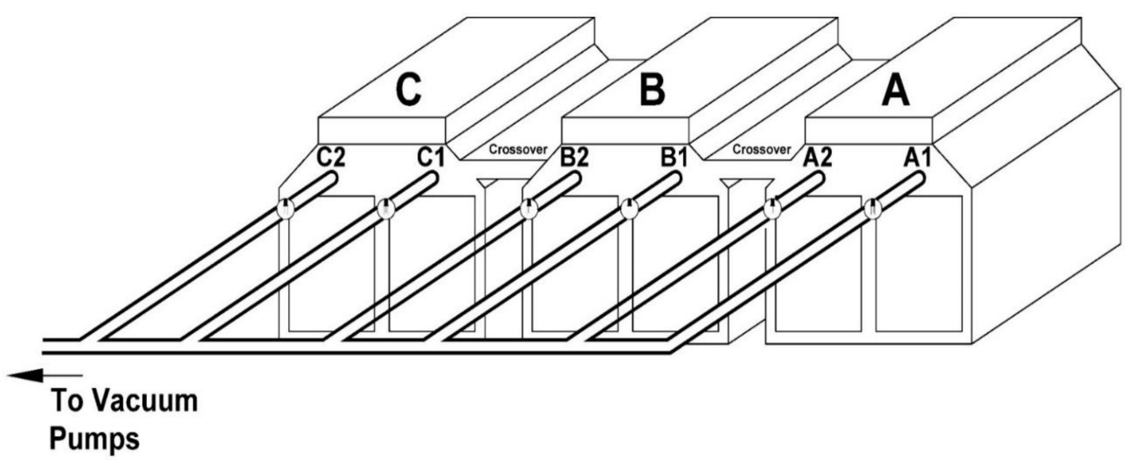

Figure 1 –Plant's air-offtake configuration

The two-probe portable *RheoVac* 951 system allowed the plant to measure non-condensable gases being removed from their 6 condenser air removal sections. Intek personnel met with plant personnel prior to testing for briefing and plant personnel expressed concerns of higher than expected backpressure. When an exhauster is shut off to measure Air In-leakage through the other operating pumps' discharge rotameter, the plant sees a backpressure rise in the condenser of approximately 0.3"Hg, which was noticeably higher since their most recent refueling outage. This data was captured and confirmed with the installation of the *RheoVac 951* equipment. The expected Air In-leakage (AIL), based on plant rotameter weekly readings, was 15-20 SCFM.

Summary of Findings

After using the *RheoVac* equipment for 1 day the following conclusions were made:

1) The *RheoVac* equipment provided proof that the rotameters were not providing reliable measurements. The rotameters indicated 1/5th of the actual air in leakage flow rate. After investigation, it was found that the flapper valves used to divert the pump exhaust through the rotameters were not sealing properly and thus diverting less than the total air in-leakage. This is a very common problem industry wide.
2) The *RheoVac* equipment provided information to narrow the search for leakage to only components connected to the outer walls of 2 of the three shells, effectively reducing the air in-leakage search area to 1/3rd of a normal unit sweep for air in-leakage.
3) The *RheoVac* equipment measured the in-service pump capacity and thus verified that the pumps were operating near to manufacturer specifications.
4) Within 12 days of using the *RheoVac* equipment, maintenance action was taken, leaks were located and repaired, and condenser pressure was reduced by 0.4"Hg for an increased generation of ~XX MW.

Leak Quantification Tests – Actions Taken

Equipment setup began on the Alpha air-offtake lines. The *RheoVac* probes were powered, and atmospheric temperature and pressure was verified. The probes were warmed up for approximately 15 minutes prior to air-offtake line insertion to prevent condensation forming when installing a cool *RheoVac* probe into a warm air-offtake line. The first *RheoVac* probe, -1, was installed into the A1 air-offtake line. Within five minutes it was displaying a stable AIL value of 41 SCFM and total (vapor and air) flow rate of 1784 ACFM, which plant personnel indicated was unexpectedly high air in-leakage. The *RheoVac*'s measured volumetric flow rate is representative of the capacity at the operating suction pressure and temperature of a constant volume device, such as a liquid ring vacuum pump (LRVP). Pump capacity is provided by the *RheoVac* and may be compared to the pump's performance curves, to indicate health of the pump. Data was collected for 20 minutes, during which time it was decided that the second *RheoVac* probe, -2, would be installed into the A1 air-offtake line to verify the higher than expected AIL readings recorded on the first probe. The -2 probe was installed into the A1 air-offtake line and showed an AIL of 41 SCFM and total (vapor and air) flow rate of 1771 ACFM within five minutes, verifying the higher than expected AIL and total flow rate, see Figure 2 below. The -1 probe was installed into the A2 air-offtake line and showed a low AIL of 2 SCFM and total (vapor and air) flow rate of 88 ACFM and measured the same pressure as the A1 *RheoVac* probe air-offtake line reading, as expected (1.35"Hg). This flow imbalance occurs as a result of the hydraulic equilibrium that must be achieved between each shell pressure and the shared vacuum equipment header suction pressure. It is common for an imbalance of flows in each air off-take to occur when air in leakage is 1) sourced by a vacuum boundary breach that is either isolated to one shell of a multi-shell condenser or 2) sourced a vacuum boundary breach that is nearer to one tube bundle in a single shell condenser. This flow imbalance information is extremely useful to reduce the search area for air in-leakage; in this case shell A and boundaries/penetrations/components connected to shell A. The air removal section A2 was being starved of flow by the large AIL at the A1 location, indicated by the low volumetric flow rate of 88.4 ACFM, data shown in Table 1.

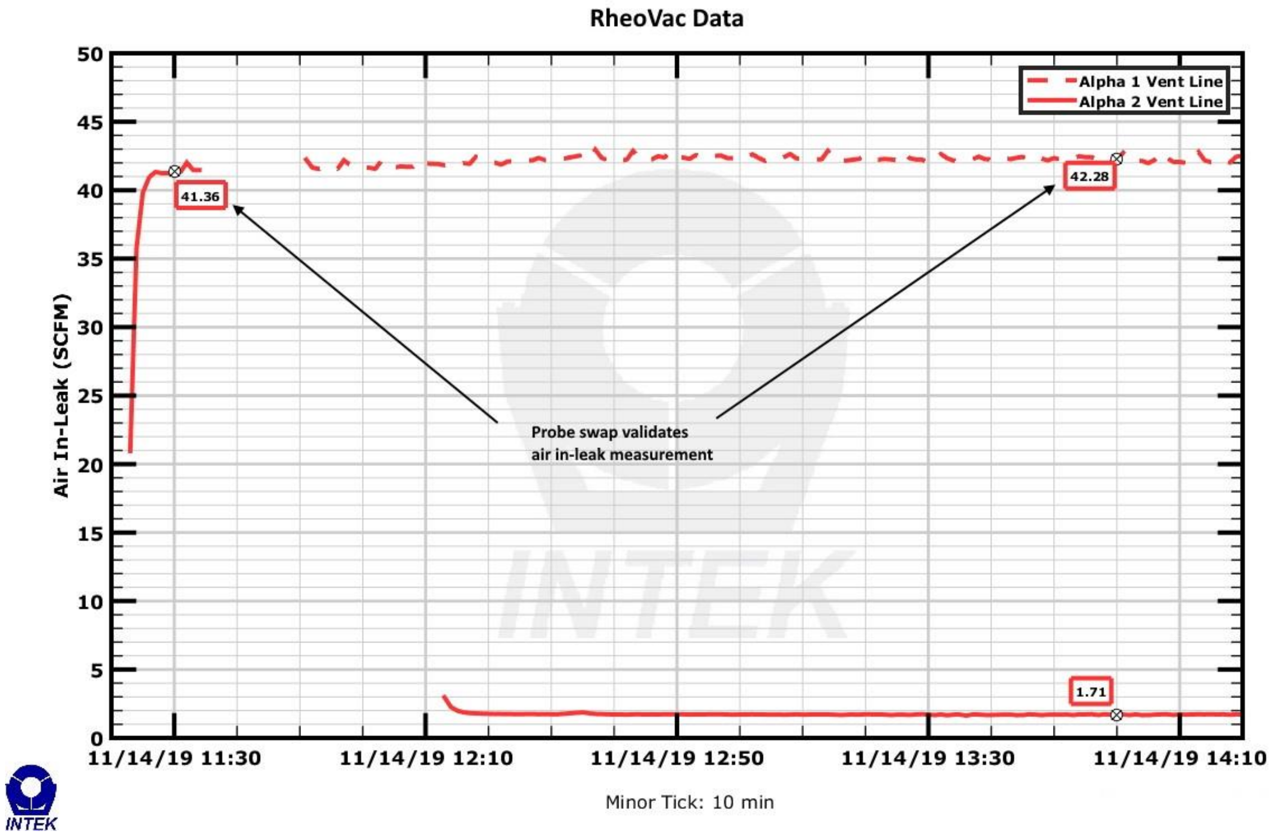

Figure 2 - Alpha condenser air in-leak data before repairs

The *RheoVac* probes were removed from the Alpha condenser's air-offtake lines and installed into the Bravo condenser's air-offtake lines. Within five minutes the probes were showing low AIL, see Figure 3 below and the both probes showed the same pressure as the Alpha condenser (1.35"Hg). The low flow data out of the Bravo condenser was very stable and after acquiring data for 10 minutes, the probes were removed.

The -1 *RheoVac* probe was installed into the C1 air-offtake line and within five minutes it was displaying a stable AIL of 50 SCFM. The pressure indicated by the probe was 1.53"Hg, a few tenths of an inch higher than what was seen in the Alpha and Bravo condensers. Note that later in the afternoon after viewing plant recorded data, there was an unexplained rise in condenser backpressure of approximately 0.2"Hg between the probe installations of the Bravo and Charlie condensers. The -2 *RheoVac* probe was installed into the C2 air-offtake line and showed low AIL, see Figure 4 below but with a similar pressure as seen in the C1 air-offtake line, 1.47"Hg. The total AIL measured by the *RheoVac* probes in all six condenser air-offtake lines was approximately 97.5 SCFM, see Table 1 below.

Table 1: *RheoVac* data recorded before repairs

	A1	A2	B1	B2	C1	C2	Total
Air In-leakage (SCFM)	42.24	1.74	0.72	1	50.4	1.43	97.53
Total Mass (lb/hr)	294.5	13.2	12.3	16.1	305	14.4	655.5
Pump Capacity (ACFM)	1784	88.4	94	121.8	1570	89.7	3747.9
MR (lb/lb)	0.55	0.69	2.82	2.43	0.344	1.23	-
Pressure (Hg abs)	1.37	1.32	1.32	1.32	1.53	1.47	

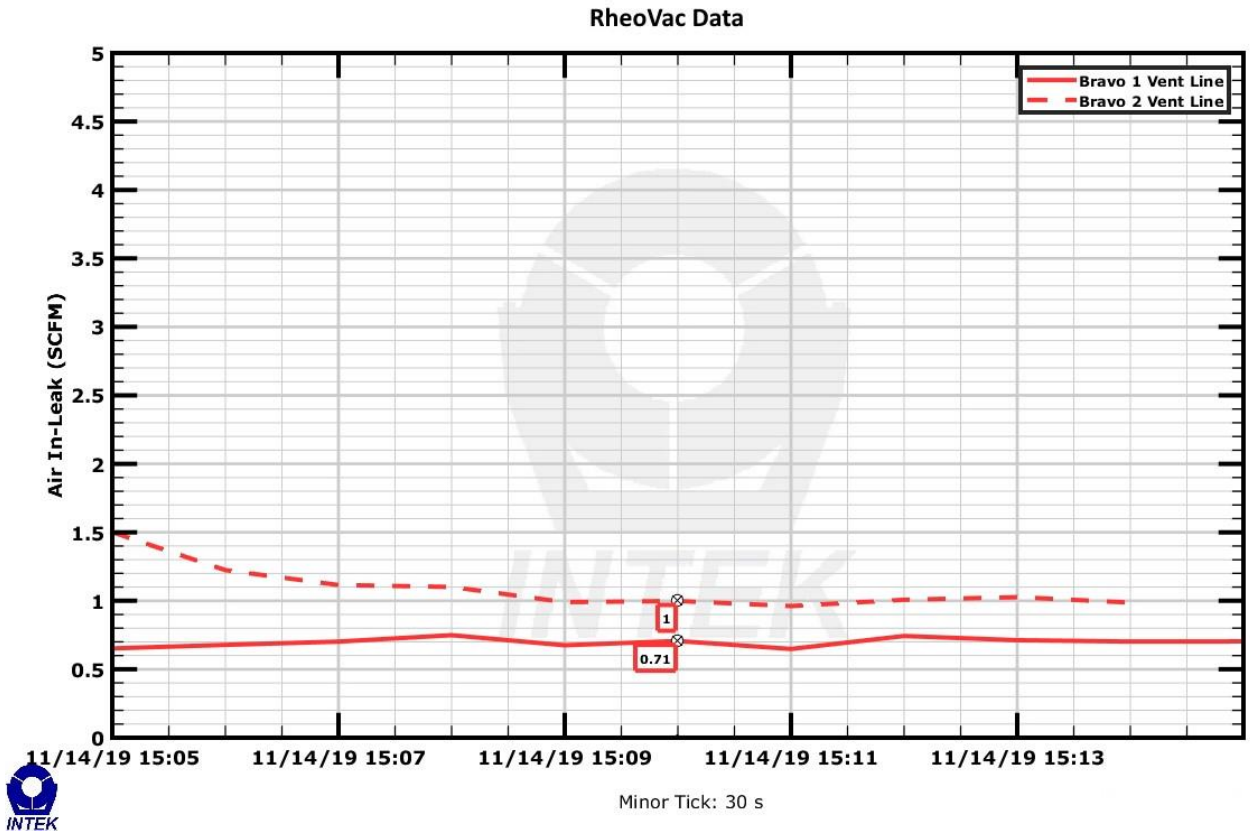

Figure 3 - Bravo condenser data before repairs

Pump Capacity Test (Pump Swap) – Actions Taken

Next the plant shut off one of the exhausters and air-offtake line pressure was observed to slowly rise. After 12 minutes of single pump operation the *RheoVac* pressure measurements were 2.28 and 2.24"Hg respectively, an increase of ~0.76"Hg. The Volumetric Flow rate was observed to drop to 878 ACFM in the C1, high AIL air-offtake line. During the single pump operation, the pump vent was diverted through its rotameter, and the rotameter reading was only 21.5 SCFM. Next the second exhauster was turned back on, and minutes later the other exhauster was shut off. After 17 minutes of the second single pump operation the *RheoVac* pressure measurements were 2.30 and 2.26"Hg respectively, and a very repeatable 884 ACFM volumetric flow rate, showing that the vacuum pumps had similar capacities, see Figure 5 below. During this second pump single operation, the pump vent was diverted through its rotameter, and the rotameter reading was 30 SCFM. It was noted by plant personnel that the flapper valve on this pump was recently replaced. The outlet of the rotameter discharges to atmosphere from the top of an approximately 1" hole and was felt by hand during the reading.

Intek has witnessed that the force used to close the flapper valve will impact the amount of air diverted to the rotameter and recommended that two men pull on the flapper valve. With two men pulling the flapper valve handle together, the rotameter float slammed to the top and became stuck. The outlet air flow felt much higher with both men pulling on the handle. With approximately 90 SCFM Air In-leakage the flapper valve is unable to be fully closed to divert all the air flow through the rotameter.

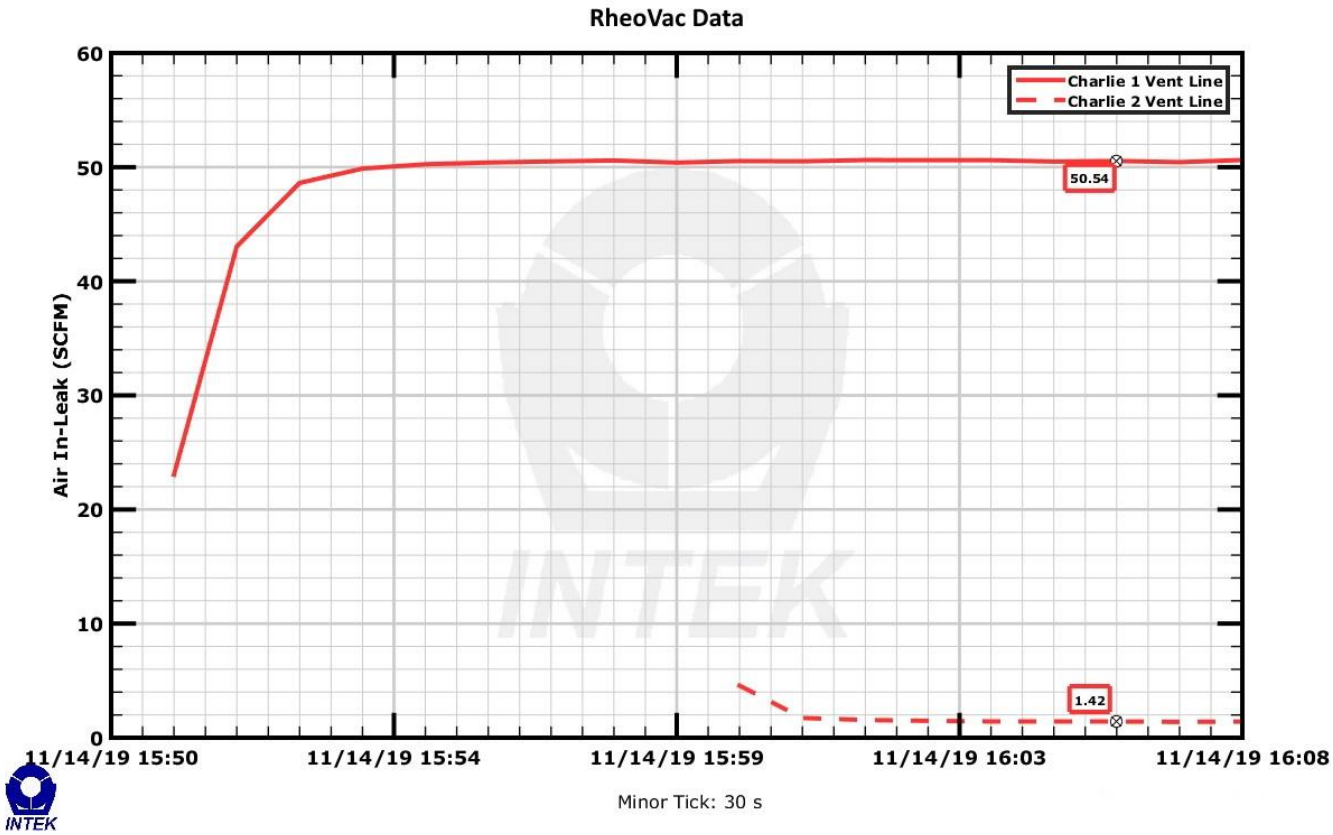

Figure 4 - Charlie condenser data before repairs

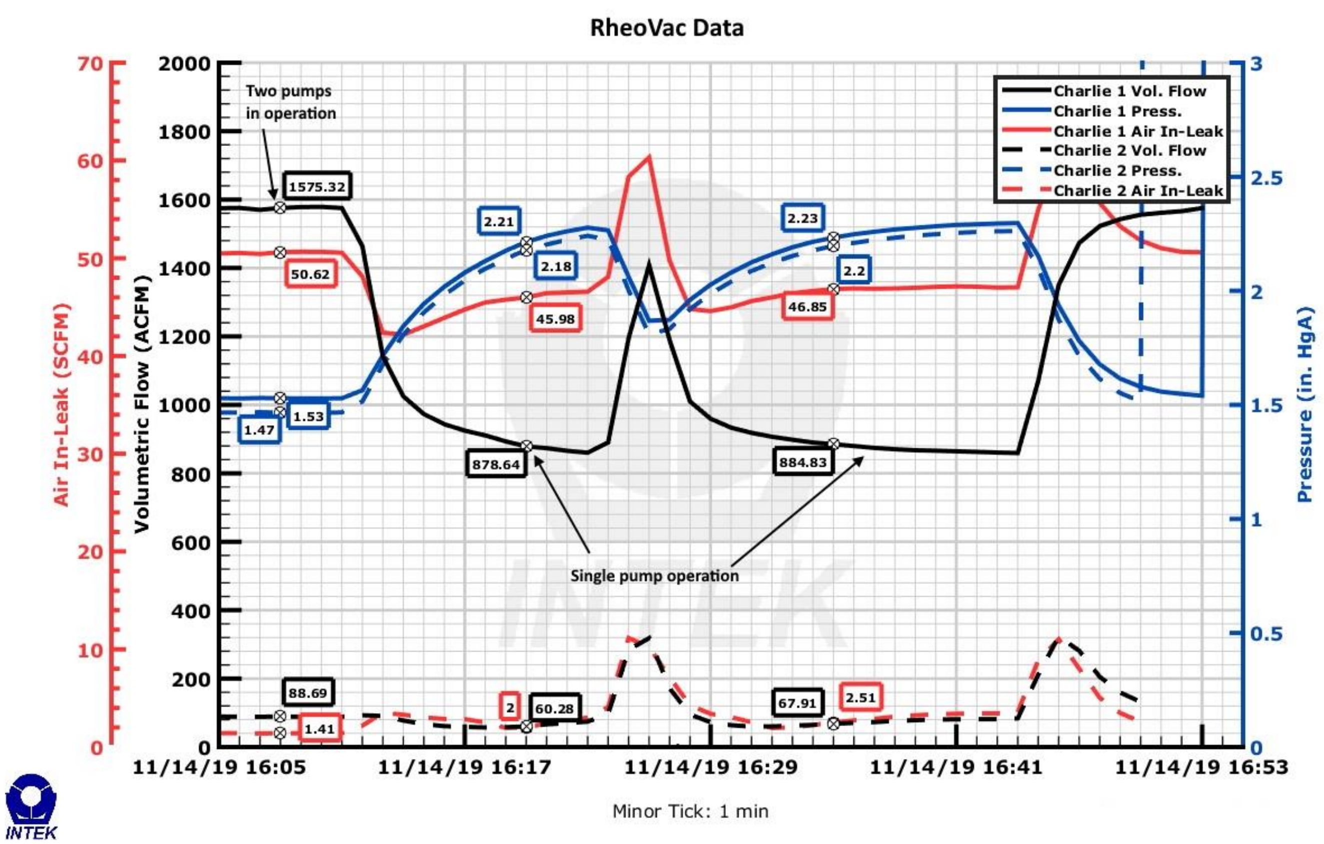

Figure 5 - Single pump operation comparison

Pump capacity calculations were performed based on available data from the pump manufacturer data for the Nash AT 3004 exhauster, assuming a seal water temperature of 60°F. This showed a capacity of 1750 ACFM per pump at the given air-offtake line temperature, pressure and relative humidity as measured by the *RheoVac* probes installed in the A1 and C1 air-offtake lines. The calculations showed an expected Total Mass Flow rate of 327 lb/hr per pump, and a capacity to remove Air In-leakage of approximately 40 SCFM per pump. This data coincides with the total flow data shown in Table 1, a total of 3747 ACFM was measured across the Alpha, Bravo and Charlie condensers, indicating the pumps are operating as expected.

Results Summary

Guided by data from the *RheoVac* system, plant personnel identified and repaired leaks in the Alpha 1 and Charlie 1 air removal sections. After completing repairs, a single *RheoVac* probe was reinstalled in all six-condenser air-offtake lines to quantify the impact that repairing the leaks had. The *RheoVac* data shown in Table 2, indicated that the repairs were successful in reducing the total AIL from 97.5 SCFM to 10.9 SCFM.

Table 2 - Data recorded after leaks repaired

	A1	A2	B1	B2	C1	C2	Total
Air In-leakage (SCFM)	2.2	1.5	0.6	0.7	0.7	5.2	10.90
Total Mass (lb/hr)	40.7	13.6	17.6	22.45	17.7	236.4	348.45
Pump Capacity (ACFM)	430	130	190	270	190	2507	3717
MR (lb/lb)	3.06	1.04	6.08	6.17	4.49	9.08	-
Pressure (Hg abs)	0.95	0.96	0.96	0.88	0.96	0.98	

Figures 6 and 7 below show the reduction in air in-leakage after repairs were made in A1 and C1 condensers and include the *RheoVac* measured parameter water to air mass ratio, the ratio of water vapor flow rate to dry air flow rate.

The value of the water-to-air mass ratio has significance in determining the vacuum system adequacy for 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. 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. Intek 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 simple air in-leakage test.

A reduction in the measured *RheoVac* pressure of approximately 0.4” Hg was observed after the leaks had been repaired and the water to air mass ratios increased to greater than Intek’s recommended level of 3 in all but the A1 condenser.

Conclusions

Using the *RheoVac* system, plant personnel were able to measure the individual AIL being removed from each of the plants six air removal sections. The *RheoVac* showed higher AIL than was expected by plant personnel, and from only two of the plant’s six air removal sections, limiting the AIL removed from the other four air removal sections. The *RheoVac* total AIL was five times greater than the AIL indicated by the plant’s rotameters, elevating the requirement to identify and repair condenser air leaks. This data allowed plant personnel to focus their search for air leaks to the A1 and C1 condensers. The volumetric flow rates measured by the *RheoVac* showed that the plants exhausters, LRVP, were performing as expected when compared to the pump manufacturers performance curves.

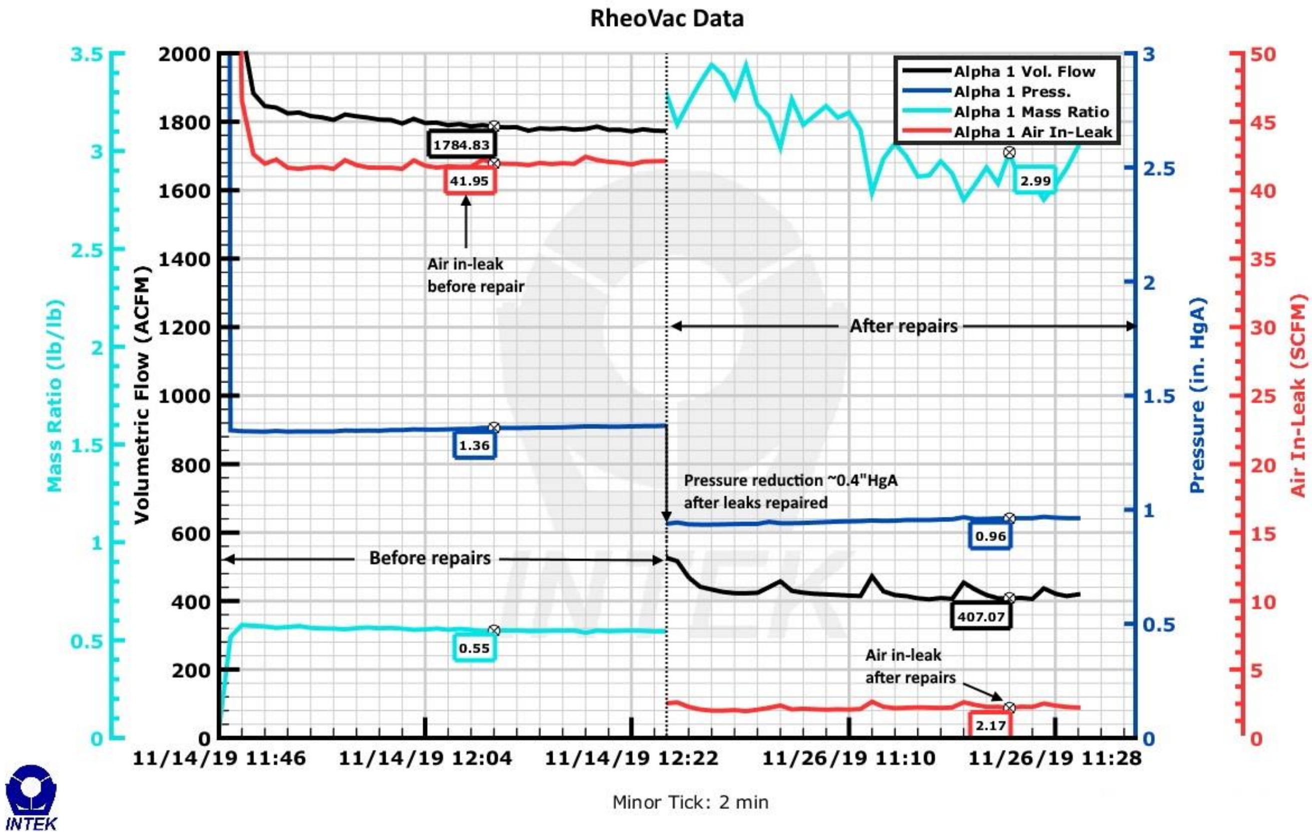

Figure 6 - Before and After Repairs Alpha 1 Condenser

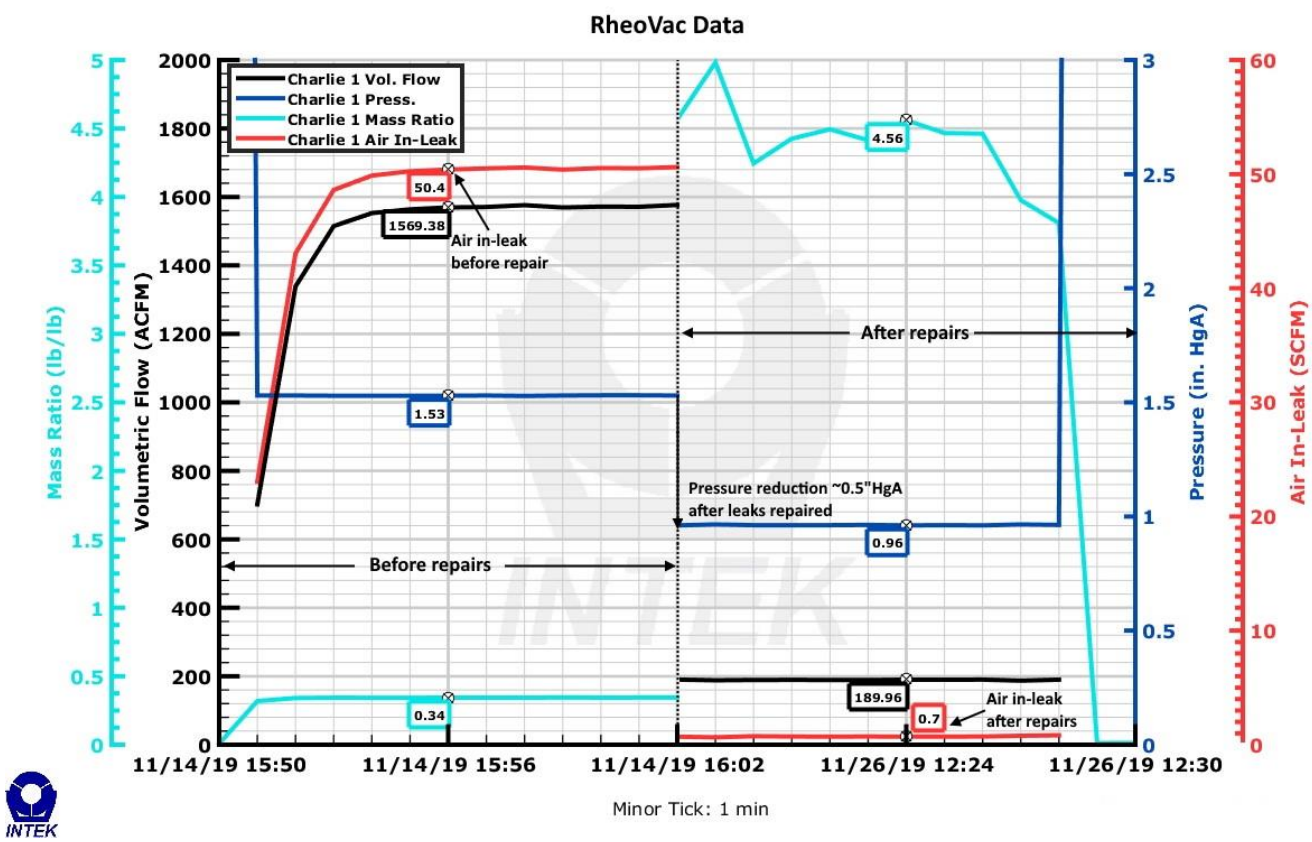

Figure 7 - Before and After Repairs Charlie 1 Condenser