Air Ingestion and Transport Testing in a Rotating Drum Raw Water Strainer

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Abstract

McGuire Nuclear Station (MNS) is performing ongoing work upgrading components and systems in their raw water supply (RN) system. The RN system supplies the cooling water for residual heat removal and represents the assured source of heat removal during emergency shut-down. At MNS, the main source of cooling water is Lake Norman but an additional ultimate heat sink pond, the Standby Nuclear Service Water Pond (SNSWP) represents the assured source of cooling water during an accident which has Lake Norman unavailable as a source for cooling water. When the RN system shifts suction from Lake Norman to the SNWP, the suction piping becomes nearly a half mile long and the inlet pressure to the strainer, which is installed on the suction side of the RN pump drops to vacuum conditions, depending on flow rate. The RN strainer is a rotating drum strainer, spinning at a constant 4.5 RPM. The motor and gear-box connection for the spinning filter element is at the top of the strainer, sealed by four rings of packing. Over time, the packing seals can wear and allow water to leak out through the packing since the strainer operates at about 10 psig (positive) under normal operating conditions. Under vacuum conditions, the water leakage out of the drum will stop and air ingestion into the drum will begin. A wide range of strainer and backwash system performance tests was conducted during the summer of 2011 at Alden Laboratory using a full-size raw water strainer taken out of service from MNS. Part of these tests concerned a quantitative determination of the rate of strainer air ingestion and an assessment as to the path of transport (if any) for the ingested air. Testing revealed that a sizeable air bubble forms on the interior side of the drum strainer, downstream of the filter elements. The air bubble appeared stable in testing under constant operating conditions and was largest at low system flow rates. When the test flow rate of the system was increased, the new stable, lower bubble volume was achieved quickly and the difference in bubble volume was transported downstream quickly. Such sudden transport of air has the potential to impact pump performance. However, a review of the plant system and operation reveals that the transient responsible for the sudden transport of air downstream is not possible. Nevertheless, the understanding gained from testing regarding the transport and accumulation dynamics of the ingested air has been helpful in better understanding what the likely impacts of air ingestion are on system performance

1.0 Introduction

The McGuire Nuclear Station (MNS) raw water system (RN) consists of four trains serving Units 1 and 2. Two of the four trains operate at all times, one for each unit, supplying component cooling water and other non-essential cooling water load needs for the plant. During certain accident scenarios and for shutdown, RN supplies the residual heat removal (RHR) heat exchangers to remove residual heat from the reactor. The water supply to the RN system must therefore be assured. At MNS, an ultimate heat sink pond serves as the assured source of cooling water when Lake Norman is unavailable.

A simplified schematic of the relevant system is shown in Figure 1. The figure correctly shows the difference in piping length between sourcing the water from Lake Norman compared to from the Standby Nuclear Service Water Pond (SNSWP).

Under normal operating conditions, the installed elevation of the RN strainer results in a positive pressure of about 10 psig at the inlet to the strainer. Under emergency operating conditions, the long suction piping from the SNSWP, coupled with higher flow rates cause vacuum conditions at the strainer inlet.

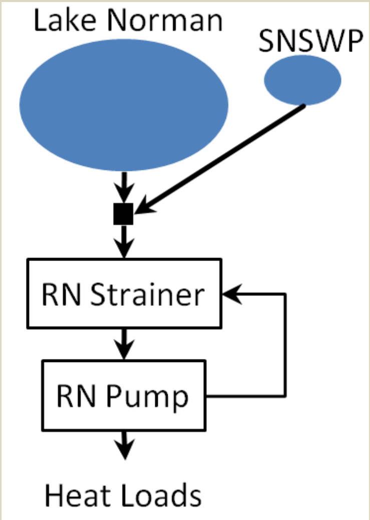

Figure 1. RN system supply

The RN strainer is a rotating drum type strainer, an example of which is shown in Figure 2. Dirty water enters the strainer and distributes up and around the rotating drum. The rotating drum is equipped with a large number of holes which contain filter media. In the case of MNS the filter media are made of perforated plate with 3/16" holes. A previous study examined the fluid mechanics and debris cleanout characteristics of the strainer [2].

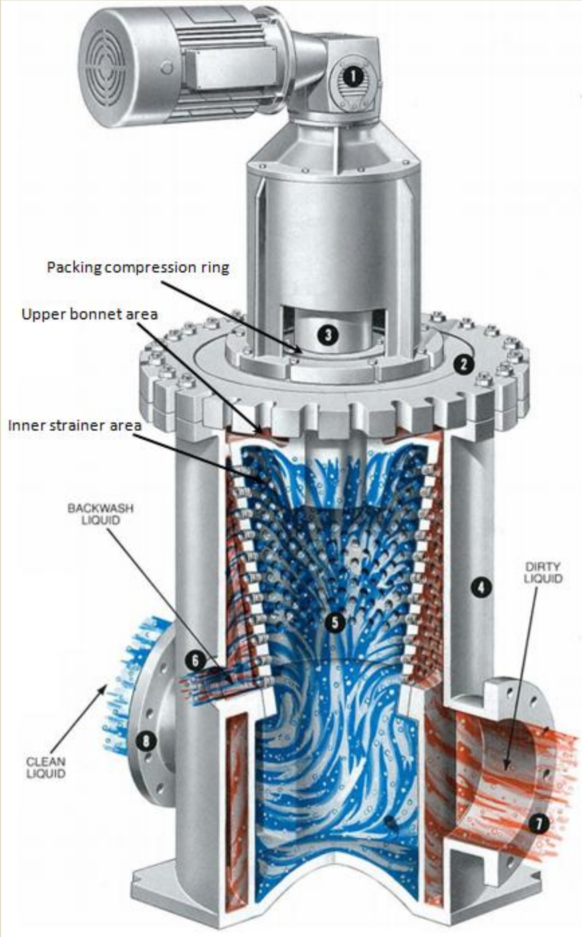

Figure 2. Rotating drum strainer [1]

The previous test sequence as well as plant observation of the older strainers currently being replaced showed that the packing assembly at the top of the strainer is susceptible to water leakage. While maintenance on the packing assembly can alleviate most of the leakage, a concern remained that the water leakage observed out of the strainer could translate to unacceptable air in-leakage under vacuum conditions.

The tests described below aim to quantify the possible levels of air ingestion and the transport characteristics of the ingested air. It should be noted that the testing was performed on a strainer removed from service after 25+ years in the plant. Packing leakage and air intrusion characteristics are expected to be very conservative relative to a newly installed strainer with properly maintained packing assembly.

2.0 Test Setup

Figure 3 shows a schematic representing the important parts of the test loop setup. Control and isolation valves have been omitted from the schematic for increased clarity. The test setup is made up of a closed loop around the test strainer. The test loop is equipped with a large centrifugal pump to drive the full range of operating flow rates through the strainer. Flow is measured with a venturi, designed and calibrated at Alden for this test. The loop has an inlet standpipe which consists of a six inch pipe extending vertically upward beyond the height of the strainer, to about 8 ft above the centerline of the pipe loop. A short length of the standpipe was transparent and a water level gauge was installed to monitor water level inside the standpipe. The transparent section allowed a visual inspection as to the quantity of air that might be getting trapped at the standpipe. For the sequence of tests described here, the standpipe was capped and connected to a vacuum pump for venting.

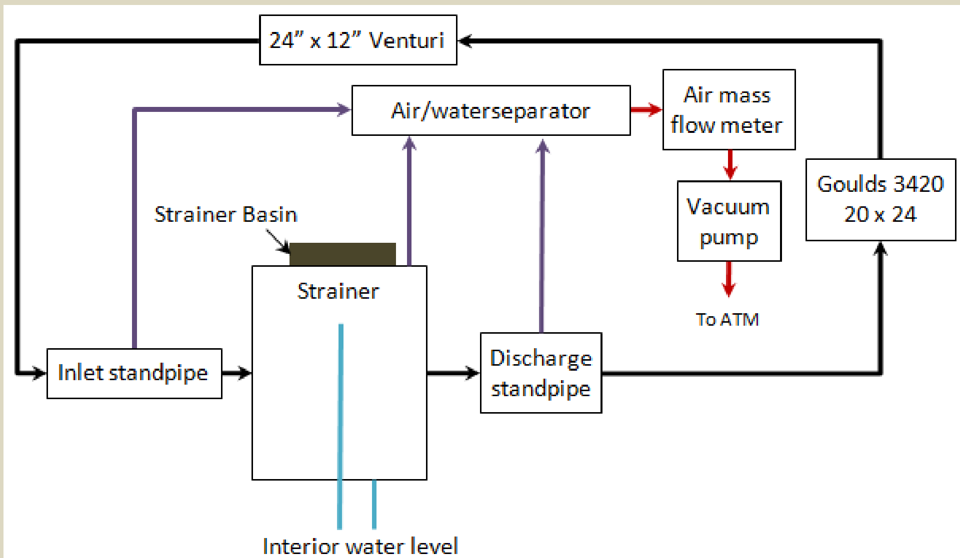

Figure 3. Test loop setup

The strainer itself was modified slightly from its condition when it was removed from the plant. Windows were cut into the steel wall to allow visual observation. A basin was installed at the top of the strainer around the packing ring area to allow a water blanket to be maintained and prevent air intrusion from the packing.

On the interior, a water level gauge was installed to measure the interior strainer water level. A long copper tube was installed into the top of the upper bonnet area. A second copper tube was installed such that it was flush with the floor of the strainer near the center of the strainer. To measure the water level, the copper tube installed into the upper bonnet area was first filled with water. The two copper tubes are connected to the two sides of a differential pressure transducer. When the strainer is full and there is no flow, both branches read the same pressure. When the strainer is full and there is flow, a small differential pressure reading may be caused depending on the local flow induced static pressures at the two sensing ports. Measurements showed this effect to be negligible. When the strainer collects an air void, the long copper tube remains filled whereas the pressure exerted by the water column on the tap installed in the floor is reduced. An indication of the void size is thus obtained.

The strainer drum was equipped with a full replacement gear box and motor, allowing the drum to be rotated at the plant operating speed of 4.4 RPM.

Downstream of the strainer a 12" standpipe was installed to collect air that is entrained into the process flow. The standpipe was also equipped with a level sight gauge. The standpipe was capped and connected to an air mass flow meter and the venting vacuum pump.

An air water separator receptacle was used to isolate the air mass flow meter and vacuum pump from any potential water that may also be withdrawn from the test loop.

3.0 Test Approach

Quantifying air intrusion for the operating strainer is complicated by the fact that there may be background sources that contribute to the measurement. Since the strainer drum spins in operation, a basin was installed at the top of the drum to allow this area to be maintained under water, thus preventing any air intrusion. Water intrusion would occur but at a reduced rate compared to air due to the higher viscosity. The test was then operated to investigate what gas withdrawal flow rate would keep the test loop pressure constant on the downstream side of the strainer. Key potential air intrusion locations were the pump seals and flange pipe connections. Initial measurements showed unacceptable leakage. Pipe connections were again tightened and the pump seals were wetted using an external water supply. These measures reduced the levels of air intrusion in the background to levels that were so low relative to the air intrusion of interest that the background air intrusion could be ignored. The persistence of these conditions was checked regularly to ensure the established seal in the facility was not deteriorating.

To measure air intrusion, the air mass flow meter and vacuum were connected directly to the strainer vent opening in the top of the strainer. This prevented void formation within the strainer (discussed below) and increased testing throughput. For each valve setting, several minutes were required to establish a steady state reading.

The packing resistance flow measurements were conducted without process flow to prevent water from being intermittently withdrawn from the port. Since only little flow travels in the relatively thin space between the top of the rotating drum and the strainer cover, it is safe to assume that packing resistance is not affected by process flow. Measurements conducted with process flow, removing the air at the downstream standpipe confirmed the resistance measurements, although steady state was a lot more difficult to maintain, in part due to the void formation phenomenon described below.

4.0 Test Results

4.1 Strainer packing leakage

The packing leakage curve obtained from testing is shown in Figure 4. The air intrusion from the packing was very significant and the vacuum capacity was exceeded at only a 1 psi differential across the packing. Plant conditions could be much worse with differential pressures reaching up to 4 psid. Nevertheless the collected data is valuable. When extrapolated to plant conditions, 74 gpm (at downstream packing pressure, 75^{o}F) is predicted to be entering from the drum packing in the present conditions. It should be noted that similar measurements were previously performed on another strainer without drum rotation and exhibited lower air intrusion. It is therefore conceivable that rotation generates a thin fluid film layer that allows a lower resistance path to form and allows air intrusion to increase. However, static measurements to confirm this behavior have not been conducted to date. The level of air intrusion observed with rotation here is still not a concern for pump operation since it represents less than 0.75% of the process flow (at 10,000 gpm) under these conditions.

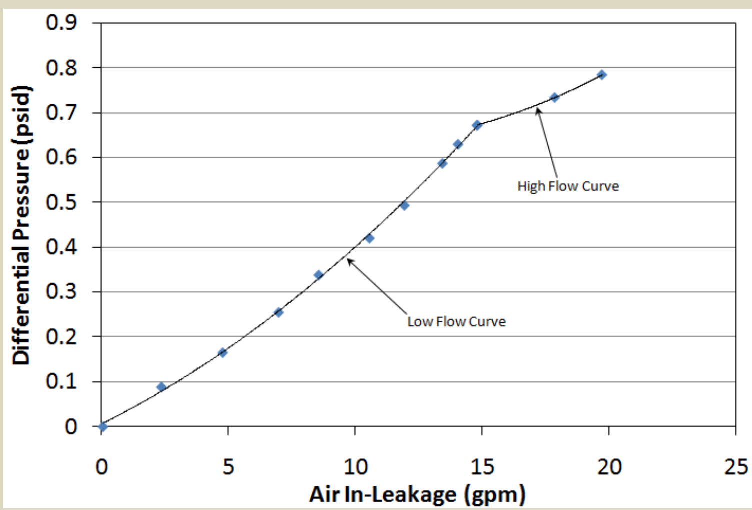

Figure 4. Summary of packing resistance measurements

Figure 4 shows that the results appear to fall along two separate curves, one for low differential pressures and another for higher differential pressures. The differences cannot be explained simply by distinguishing a turbulent from a laminar regime. Both flow curves are quadratic and therefore are likely to involve turbulent flow. The thin gas passages between the packing and drum shaft involve relative rotational motion and the dynamics of such a flow can be very intricate and complicated (e.g. Görtler vortices [3]).

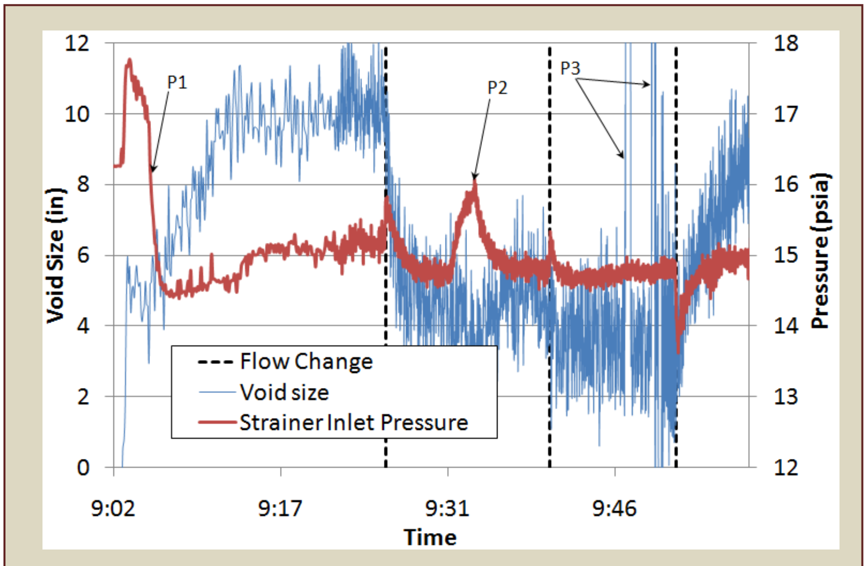

Figure 5. Part 1 of air transport test

4.2 Air transport testing

After characterizing the flow resistance of the packing installation, testing was conducted with process flow to develop an understanding of how the air introduced to the strainer is transported or stored. Previous testing showed the potential for void formation in the RN strainer. The present test effort was aimed at clarifying the conditions and size of the void formation. While several tests were conducted to determine the fate of the ingested air, the phenomena observed were very consistent and can be examined for the most part using a single test sequence as an example. The test sequence is divided into two parts for additional clarity.

Figure 5 shows the first part of the test. The figure shows both the RN strainer inlet pressure and the void indicator described above. The figure also marks several points during testing which are labeled P1, P2 and P3. P3 identifies points where the void indicator sensing lines were bled. Changes in flow rate are indicated by black vertical dashed lines. It should be noted that at approximately 9:19, the visual void indication manometer board was isolated to prevent potential emptying of the high side of the sensing lines.

The RN strainer was initially bled out to be water solid. The main pump was then started with the well at the top of the RN strainer dry. The flow rate was close to 6000 gpm. P1 indicates the point at which vacuum operation was begun. The RN strainer pressure is seen to decrease. Immediately upon decrease of the RN strainer inlet pressure the void gauge began to register an increase which eventually built to a level difference of approximately 10 inches. No void was indicated on the inlet side of the drum by two different sight gauge lines. The void was therefore located within the drum. One likely reason no void was observed on the inlet side was the pressure differential across the drum (about 1.8 psid at 6000 gpm for this test). The flow resistance of the drum is high enough to require the entire inlet surface of the drum to wet on the upstream side. However, flow resistance downstream of the drum is low and velocities at the top of the drum are also low allowing the air to accumulate.

The air appears to travel through the packing and then is entrained by the flow surrounding the drum, being eventually pushed through the drum where the air can accumulate due to much slower velocities. The flow is likely bubbly. Once an initial void is formed, air is more and more easily separated from the water. The separation becomes easier because the existence of the void causes the water to be sprayed through the media making it easier for the bubbles to separate from the water, releasing the air from the flow stream. Void formation is limited by the ability of the flow inside the drum to entrain the air being pushed through. As the water level drops, velocities inside the drum increase allowing entrainment to increase. The void stops increasing in size when there is a balance between air ingestion and air entrainment inside the drum.

Note that during the formation of the void, the RN strainer inlet pressure initially increased. The increase in pressure can only be explained by a short term decrease in the flow resistance of the drum packing. These changes depend on the cleanliness of the water in the well and the area around the packing. While every effort was made to begin the overall test program with a clean well, grease and other crud from the RN strainer continued to be produced causing the material to be available for entrainment into the packing under vacuum conditions. When the material eventually gets expelled or fully absorbed, the resistance of the drum packing decreases once again.

The void size monitor signal was relatively noisy. The RMS observed was not due to sensor noise but is an indication of the dynamic water surface inside the drum. It was also not possible to determine whether the void is symmetric but drum rotation and the low mean velocities at the top of the inside of the drum can be expected to generate a nearly symmetric void. Drum rotation also contributes to the water level dynamics within the drum and the high RMS void size reading. Even while the signal itself was noisy, it is clear that the void presence is stable. Once the water initially displaced by the void was removed from the downstream stand pipe, the steady state condition withdrew only air. There does not appear to be any long term drift in the size of the void. There is no indication that the void has the potential to collapse suddenly under steady operating conditions.

The first indicated flow rate change marks an increase in flow from 6000 gpm to 8000 gpm. Void size is seen to decrease very suddenly. During testing a correspondingly fast drop in the downstream stand pipe water level was observed. The drop occurred over the time required for the main pump to spool up to the higher speed, i.e. 1-2 seconds. The test demonstrates that a large pocket of air did exist within the drum and was swept downstream with the increase in flow. The void level continued to evolve over several minutes stabilizing at approximately 5 inches.

Point P2 indicates a short time during which vacuum pump operation was ceased and loop pressure was allowed to increase. During this time, the rate at which air is ingested by the RN strainer decreases while the velocity inside the drum remains the same. The difference between the rate of supplied air and the rate of entrained air therefore causes the void to deplete. When vacuum operation is restored, the void reforms to the original size. While the vacuum operation was secured, the air being removed from the RN strainer void could be observed in the form of a dropping downstream standpipe level.

The second dashed black line indicates a change in flow rate from 8000 to 9500 gpm. As in the previous increase in flow, the void size again decreased quickly and the downstream standpipe level was seen to decrease simultaneously. An equilibrium void size of 3 inches was reached relatively quickly. The final flow change shown in Figure 5 returned the flow rate to 6000 gpm. The void size began increasing immediately back towards the previously observed steady state condition of 10 inches.

The development of the void and loss of water column pressure on the downstream side of the rotating drum should cause an increase in RN strainer differential pressure. The correlation is most obvious when examining the differential pressure history of the formation of the largest void. Figure 6 isolates a time period similar to that shown above. While the initial increase in differential pressure could be caused by pass-through debris slowly being caught by the drum (due to residual debris in the loop from previous debris testing), the differential pressure increase observed upon decrease of process flow later cannot be explained in the same way. The differential pressure increase is clearly a direct consequence of the formation of the void within the RN strainer drum.

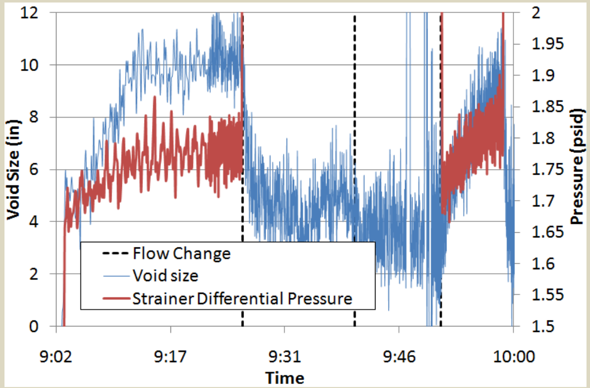

Figure 6. Correlation between RN strainer DP and void formation

Note though that the RN strainer differential pressure change was not measured to be equal to the void size but significantly smaller. (The strainer differential pressure is greater than 2 psid between the two low flow periods shown and therefore does not appear on the plot of Figure 6).

Figure 7 shows the second portion of the same RN strainer air intrusion test. The void that had reformed, nearly to full size, by moving flow back to 6000 gpm is quickly removed by an increase of flow rate to 8000 gpm. The void size formed was similar to the size developed previously. A further increase in flow to 9500 gpm caused a slight further reduction in void size, as expected. Flow was then reduced again to 6000 gpm causing void formation to begin very quickly. At the time marked P4, the RN strainer well was filled with water. The result of eliminating air introduction via the drum packing is that the vacuum pump is able to dramatically decrease the RN strainer inlet pressure. However, the void was maintained. At these much lower pressures a new balance was set up between air in-leakage into the system (dominated by the main pump packing) and the withdrawal at the downstream stand-pipe. The transport of air from the drum by entrainment was replenished by the air transported to the RN strainer from the main pump.

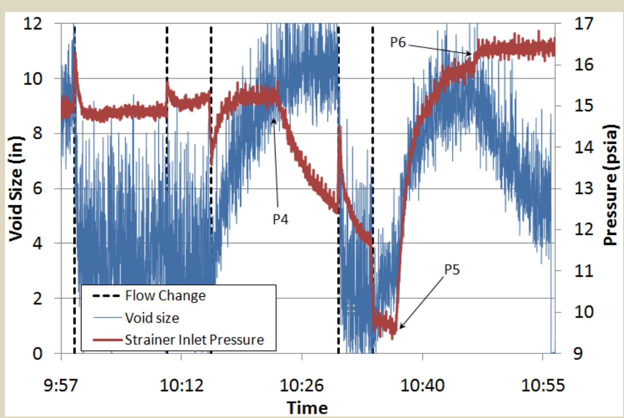

Figure 7. Part 2 of air transport test

Flow was then increased from 6000 gpm to 9000 gpm. The air in the RN strainer void was immediately transported downstream with a small void remaining, somewhat smaller than observed previously at nearly the same flow rate. It is possible that the higher flow rate does not allow as much air transported into the RN strainer through process flow to be trapped at the top of the drum. In contrast to air being introduced through the packing, air coming in with process flow is likely better distributed in the flow and not concentrated near the top of the drum.

Flow was then reduced again to 6000 gpm and the fluid in the RN strainer well was no longer replenished. Even while the well still contained water, the void begins to grow again, fed by loop air in-leakage. However, at point P5, the well runs dry and both inlet pressure and void increased very quickly as the air supply was dwarfed by the flow's ability to entrain the air rushing in. The void quickly formed to nearly full size again. At point P6, vacuum operation was stopped to allow the loop to come to equilibrium with the top of the drum acting as the pressure controlling point. The pressure increased slightly upon securing vacuum pump operation. At the same time, the void began to shrink as the air supply was now removed from both the loop and drum packing sources. The slow decrease in the void fraction demonstrates the relatively slow rate of air entrainment that exists at the relatively low flow rate of 6000 gpm.

The test evolution shown in the preceding graphics demonstrates the ability of the RN strainer to maintain a void as dictated by a balance of supplied air and the ability to entrain the air at the outlet of the drum. The void size is therefore not strictly a function of flow rate but also a function of the magnitude of the leakage. While the steady state void formed in the present environment was relatively small at 9500 gpm the size appears to at least partially be a function of the maximum removal rate capability of the present system.

Based on the above arguments it should therefore be possible to generate a greater RN strainer void even at higher flow rates if the pressure differential at the top of the drum is correspondingly higher. Plant vacuum differentials could be significantly higher than those tested here. Void formation should therefore be expected for a similar resistance packing configuration. To attempt more significant void formation under high flow rate conditions, the drain water pump, connected to the process loop, was actuated during testing. The volume removal could not be carried on for an extended period of time because the downstream standpipe would fill with air unable to be removed by the volume management system. Even the short term operation did show indication of an increased void being formed within the RN strainer under lower pressures. However, void formation appears to have only a small impact on RN strainer differential pressure. Furthermore, voids formed are stable with constant operating conditions. Any void is therefore unlikely to adversely affect RN system operation.

5.0 Conclusion

The following are the conclusions that can be reached for air in-leakage testing conducted on the rotating drum strainer:

1) Packing air resistance is lower when the drum is turning compared to static conditions. While rotation increases the path length air must travel it also appears to create a thin gap between the moving surfaces for air to move through.
2) Measurements indicate that air in-leakage could be as high as 72.4 gpm (using RN strainer packing pressure as density reference, 75F). The value is likely conservative because it does not account for compressibility. Even this level of air intrusion does not threaten system operation since it only represents less than 0.75% of the process flow.
3) Ingested air is transported downstream under equilibrium conditions but these conditions involve the possible formation of a void within the RN strainer. Void formation does not occur on the inlet side of the drum. Voids were only observed within the rotating drum.
4) Void size within the RN strainer represents a balance between air ingestion at the packing or other upstream system locations and the air entrainment capability of the flow on the inside of the drum. Higher flow rates can entrain more air within the drum and cause the void formed within the drum to be smaller for the same RN strainer operating pressure.
5) The void can be removed quickly by increasing the flow rate quickly under relatively constant pressure. A rapid flow increase can send a large fraction of the air contained in the void downstream. The operating sequence of test or emergency operations with the drum aligned to the pond should be reviewed to examine whether the procedure is robust to the sudden movement of air downstream. Both the RN strainer inlet pressure and the air entrainment rate capacity within the drum are a function of the process flow rate for plant conditions. The inlet pressure drop is a function of the square of the velocity and therefore flow rate. Similarly, air entrainment within the drum can be associated with the kinetic energy of the flow within it and is therefore also related to the square of velocity and consequently flow rate. It is therefore difficult to envision a plant transient that would cause the air contained in the void within the drum to be flushed out quickly.
6) Apart from changes in flow rate, the void is stable within the drum. Testing showed that when the air in-leakage path is removed by increasing loop pressure, the void is eroded over time based on the entrainment capability of the flow within the drum. The air entrainment rate decreases from steady state void operation until the void is entirely consumed. No increase of air flow downstream of the RN strainer is expected during this transient.

Acknowledgments

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