PAPERMAKING BEST PRACTICES WITH VACUUM-DEWATERING SYSTEMS

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ABSTRACT:

Vacuum systems are essential for papermaking, and contribute to sheet formation and dewatering, press performance, felt conditioning, and general machine efficiency. The vacuum system includes several sub-systems for vacuum control, air/water separation and vacuum pump seal water management. These systems can incorporate liquid-ring pumps, low vacuum fans, single and multi-stage centrifugal blowers, or hybrid configurations to complete a vacuum system.

Generally, paper machines operate with little attention required of the vacuum processes. But, these systems tend to evolve, intentionally or unintentionally, into processes with lost performance. The result is often reduced dewatering capability having a direct impact on paper machine efficiency and operating costs. Other problems can include vacuum pump reliability and maintenance problems contributing to downtime. This presentation will cover common issues found in these systems which can have a major impact on dewatering processes, quality and energy efficiency.

DISCUSSION:

Just when we think innovation is slowing down we are presented with the latest electronic gadget, self-driving cars, and some unique little tool at the hardware store. Innovation may not seem to advance as quickly with paper machines, and even when this does happen there are hundreds of paper machines which are not going to be upgraded or rebuilt. Meanwhile, paper is still being made and profits are being enjoyed on most of these machines.

The point to be made is that the newest processes are not absolutely required to produce high quality paper, board, pulp and tissue products. However, optimization of existing processes is essential.

Observations from having been exposed to almost 1000 paper machines in over 320 mills in 11 countries has revealed several papermaking facts. These include:

- You can get the sheet to the reel with a poorly performing vacuum system.
- Depth of papermaking knowledge is decreasing in most mills.
- There is often a misunderstanding of how an optimized system is intended to operate.
- There is little relationship between new and modernized papermaking systems and efficient production of high quality paper products.

Resolving any of these issues can be aided with full blown training efforts combined with gathering experts in all areas to participate in paper mill audits. Then, follow-through and management of massive lists generated in the audits will be necessary and eventually improvements are measured and everyone is happy.

An abbreviated and effective version of this effort is to choose some of the primary processes having the most impact on papermaking and examining them for application of BEST PRACTICES. With respect to the Vacuum-Dewatering systems, some of these best practices will be reviewed. While creating a useful list of best practices, they tend to fall into two categories. These are Process and Management.

Process BEST PRACTICES are those which are of a technical nature, where calculations may be necessary to provide recommendations for optimization. Management BEST PRACTICES are those related to personnel, mill procedures and culture, and employee expectations. The best processes may not be well managed, while the best management may provide superior operation of older processes.

PROCESS BEST PRACTICES:

<u>Understanding and Monitoring Sheet Formation and Table Dewatering</u> – It is surprising how often problems are uncovered in low, medium and high vacuum dewatering elements on all types of formers. These are noted as problems on 90% of systems studied.

Problems associated with early low vacuum dewatering through high vacuum flatboxes include:

- Lack of understanding of how these systems are intended to operate
- Lack of accurate vacuum measurement and control
- Lack of analysis of data presented in drainage studies
- Effect of poor operation and obsolete high vacuum elements on table drive load and forming fabric life

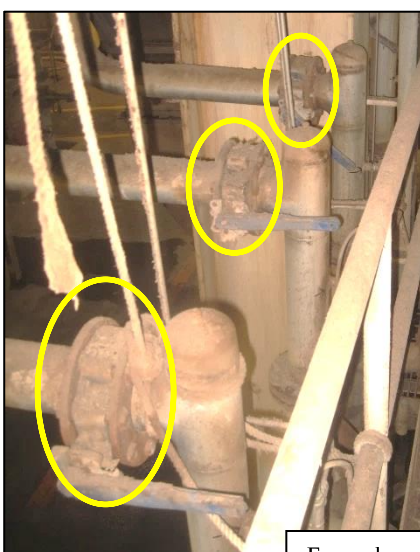
Entire technical sessions have been presented on this topic, but, a few basics follow for consideration.

Early vacuum table operation, formation, and sheet sealing are generally related. Many fourdriniers are found to have uncontrolled and aggressive dewatering occurring at the initial one or two low vacuum elements. Sometimes this can be observed visually, where stock is jumping almost a foot high beginning at the first vacuum slot of an early vacuum element. Other times there is evidence of this problem where vacuum piping is pulsing at a vacuum element, or significant whitewater is observed to be flowing from small separators or even from separator seal tanks prior to low-vac fans. These physical observations are quickly confirmed with a table drainage study. It is not unusual to find that one low vacuum element is removing 10 – 30% of the total headbox flow.

Two common problems are found with these systems are:

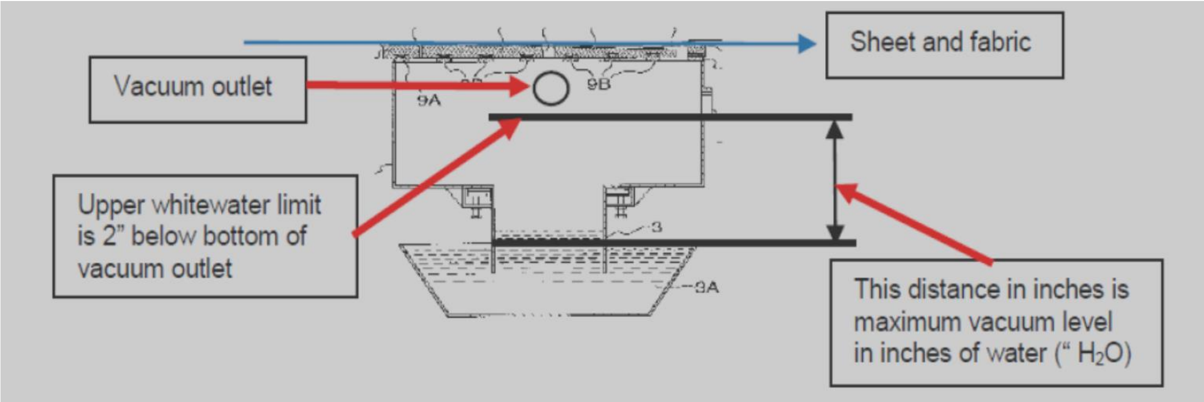
- Lack of vacuum measurement and control
- Exceeding physical vacuum or hydraulic limits of early vacuum elements

Many paper machines have evolved poorly where vacuum levels were originally indicated with manometer panels or gauges. These were combined with manual, remote operated and automatic valves for vacuum control. Eventually, vacuum instrumentation was no longer maintained and control valves failed. This often resulted in all low-vac elements being operated with most or all valves fully open. This applies full header vacuum to every element connected to that header. Where good formation requires gradual dewatering to develop the sheet, failure to control early vacuum elements creates aggressive dewatering. Besides contributing to formation problems, sheet sealing can occur which can influence dewatering down the table.



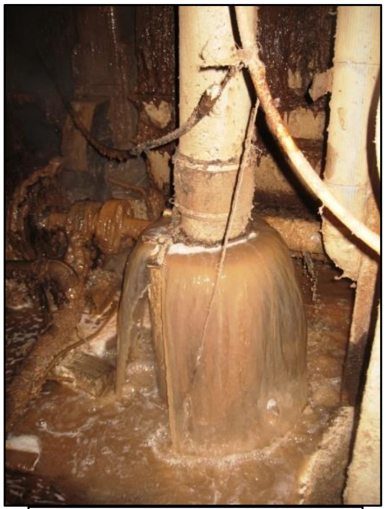
Examples of manual low-vac control

Maximum vacuum operation of any low vacuum element is easily determined by measuring the elevation of the vacuum outlet above the seal pot whitewater overflow. This can be as little as 12” to maybe 40”. Allowing 2” of maximum whitewater limit below the vacuum outlet, the resulting measurement is the vacuum limit in inches of water (“ H_2O). This is shown in the graphic below.



Evidence of exceeding maximum vacuum of a low vacuum element can often be observed on the back side of the table. Where small separator drop legs may have seal tanks, and not just dump into the wire pit, whitewater can be seen flowing into these tanks. Also, when significant whitewater is passing through low vacuum piping and flexible connections, the piping and separators will often shake or pulse as a mixture of air and water is passing through the piping.

Note, proper operation of these low vacuum elements is to operate without any whitewater flowing through the vacuum outlet. If significant whitewater is passing through the vacuum outlet this will create vacuum fluctuations and can cause CD and MD dewatering variations.



Separator seal tank overflowing indicating flooded vacuum foil element

High vacuum dewatering is applied near the wet/dry line, after formation is complete. At this point higher vacuum can be applied to dewater the sheet prior to the couch. Often there are too many flatboxes and/or too much slot area. Where two flatboxes and a tri-vac are operating these can often be replaced with only a tri-vac with a modified cover. Generally, flatboxes do not need more than 6 slots and slot widths are usually decreased as the sheet approaches the couch. Gains in flatbox vacuum are provided when flatbox vacuum zones are removed and slot area is decreased. More vacuum capacity is usually not needed to increase flatbox vacuum levels, adding to additional dewatering.

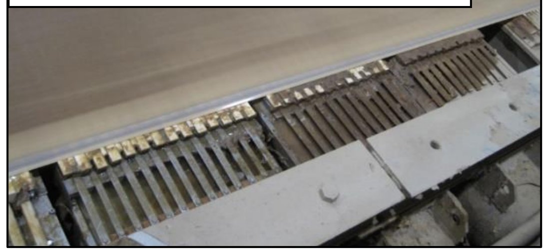
Coinciding with efforts to increase flatbox vacuum, be aware of limits for maximum vacuum levels due to the elevation of the flatbox separator above seal pits in the basement. Also, as vacuum airflow is concentrated with fewer flatboxes, vacuum separators and vacuum piping may become undersized.

Besides improved dewatering with fewer flatboxes, less slot area, and higher vacuum, table drive horsepower is usually reduced. Reworked flatbox covers using modern low drag ceramics, such as silicon nitride, will add further to reductions in table drive horsepower. This can easily be 10 – 20% power being saved among couch, wire turning roll and other former drives. This is mainly due to less friction and forming fabric life can be improved.

Evaluation of high vacuum dewatering usually allows removal of a portion of these elements and reduction in slot area of remaining elements. These modifications must be combined with changes to vacuum separators, controls and piping

Appropriate Best Practices for the table vacuum system include:

Flatboxes with excessive quantities of slots



- Maintaining accurate vacuum measurement and control for every element
- Understanding how the early vacuum table should be set up
- Observe physical maximum limits for vacuum levels of low vacuum elements
- Vacuum-dewatering optimization effort where sheet consistency is measured down the table while vacuum is adjusted to yield good distribution of water removal, and use of the entire length of the table to form and dewater the sheet.
- Eliminate unneeded flatboxes based on results and analysis of vacuum-dewatering trials
- Eliminate use of old flatboxes with excessive quantities of slots and large slot widths. Replace covers with low drag/friction ceramics such as silicon nitride.

<u>Applying Correct Slot Area to Uhle Boxes and Measurement of Uhle Box Flows</u> – Uhle boxes are essential for efficient press operation, but issues are often found with excessive slot area resulting in decreased dewatering capability. This is noted as a problem on 50% of systems studied.

Problems associated with uhle boxes include excess slot area and sometimes excess uhle boxes. Impact on papermaking can include:

- Reduced uhle box dewatering rates
- Felt shedding and damage
- Limited press exit solids

Uhle box design is pretty simple. Slot area is based on machine speed where 2 milliseconds of dwell time is adequate per uhle box. For example, this yields a total slot width of 1” for a machine speed of 2500 fpm. There is usually no benefit in having additional dwell time because this only adds to vacuum pump capacity and horsepower requirements.

The slot width yields a slot area that is multiplied by a vacuum factor to provide a necessary vacuum airflow per uhle box. This vacuum airflow is used to size the uhle box, piping, separator and vacuum source. A vacuum factor range is 15 – 20 cubic feet per minute, per square inch of slot area (cfm/in^2).

Using the 2500 fpm machine speed example requires 1” of total slot width per uhle box. A 250” felt will require approximately 4000 – 5000 cfm per uhle box. There is no practical reason to have different uhle box designs and slot configurations within the same press, unless only a portion of the press was upgraded. The only decision remaining is to have one or two uhle boxes per felt.

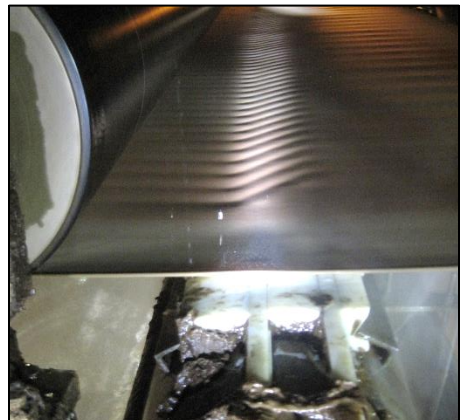
Generally, a pick-up felt will have two uhle boxes since that felt is carrying the most water and is often passing through two press nips. Correct operation with two uhle boxes per felt includes a good lube shower between the uhle boxes to rewet the felt and allow more fiber and filler to be removed at the second uhle box. The remaining felts need to be examined for felt cleaning and dewatering requirements. Two uhle boxes per felt is usually applied where felt cleaning is needed, not for additional felt dewatering. An existing press with two uhle boxes on a 3rd press felt can often have one of two uhle boxes removed. Measurement of press fabric water permeability and moisture scans are helpful in determining cleaning and conditioning effectiveness. Examining used felt analysis reports also provide information to aid this evaluation. Generally, if felts are not filled at the end of their life, then single uhle boxes are likely adequate.

Many people feel they need herringbone or zig-zag uhle box covers when using seamed felts, and this is generally not true. Seam designs have improved greatly over the 25 years since their introduction and straight slots are usually acceptable. <u>There are many 4000+ fpm machines running 6 and 7 weeks on seamed felts with slotted covers</u>. Considering nip cycles, this is comparable to running over 10 weeks on an average linerboard machine.

Adding another useful tool is essential to press optimization, and this is <u>measurement of uhle box and press nip flows</u>. This feature exists on the best running paper machines in the world. Note that this is not limited to the newest machines, because this capability is easily and economically added.

The easiest flow measurement method is using existing seal tanks having V-notch weirs and fitting these with level transmitters whose data can be calibrated to provide flow rates. Each felt should have its own weir and flow rate value. Some mills have installed flow measurement devices such as Ecoflow™ to provide the same information. Where vacuum separators may have extraction pumps rather than drop legs, a flowmeter can be used for each pump.

Straight slots are often suitable for uhle boxes, even with seamed felts



Herringbone covers frequently have excessive slot area

Creating the ability to measure and trend all press water removal, and being able to classify where the water came from (uhle boxes or nips) provides valuable data for press optimization. Informed decisions can be made regarding felt design, roll cover materials and designs, chemical cleaning of felts, and managing nip dewatering are results from accurate press water flow measurement.

Typical seal tank with weirs – can easily be modified with addition of level transmitters

Ecoflow™ for measurement of uhle box and press nip flows

A summary of felt conditioning and dewatering Best Practices are:

- Minimize uhle box slots to not exceed 2 milliseconds of dwell time per uhle box
- Verify herringbone slot areas are not excessive
- Maintain vacuum factors of 15 – 20 cfm/in^2
- Measure and trend uhle box and nip weir flows
- Combine optimized fabric conditioning and dewatering with analysis of water removal rates to maximize press water removal performance using informed chemical cleaning programs, felt designs and roll cover design choices.

<u>Operation of Vacuum Pump Seal Water Systems</u> – Vacuum pump seal water is generally ignored until significant problems are causing vacuum issues. Where seal water is recirculated and cooled with a cooling tower, most mills are not aware of developing issues in these systems. Where seal water control can have variations with less impact to pump performance, cooling tower systems are often found to be out of control.

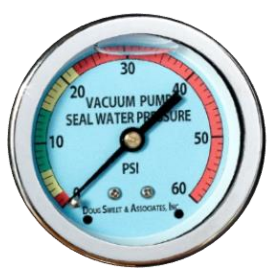
Problems associated with seal water systems can include:

- Lack of understanding of how these systems are intended to operate
- Little or no instrumentation for control of seal water
- Little or no monitoring of recirculated seal water quality
- Poor condition of cooling tower

Operation of liquid ring vacuum pumps is relatively simple. The pumps need to operate at a relatively low speed range, in the correct direction, and seal water must continuously be flowing through the pumps. Even if only 20% of the standard flow rate is used, vacuum airflow will be created. At 200% of standard seal water flow, vacuum airflow is occurring but operating power will be increased due to higher water rates. Basic principles are used to control water flow.

Each pump model has a normal or standard seal water flow requirement. Too little water decreases pump performance and too much water adds to pump horsepower. The standard rate can vary by ±10 – 20% with little impact on performance. Therefore, precise flow control is not necessary. Generally, water flow is controlled with spray nozzles and orifices selected for a specific supply pressure to deliver the correct flow rate. Most vacuum pump suppliers use 10 psi as the target supply pressure because this low pressure results in larger orifices and nozzles which will reduce the potential for plugging these components.

Seal water orifice union – note s/s tab

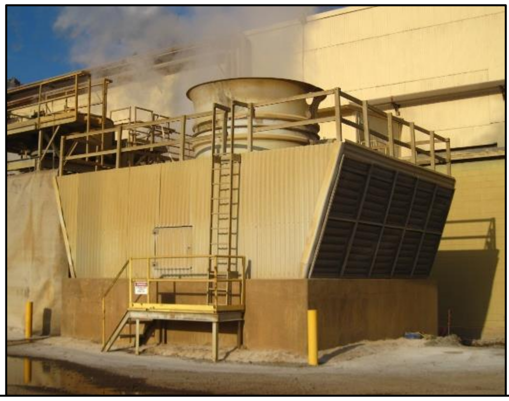


Unique seal water gauge

Someone has verified orifice locations

New vacuum systems are usually installed with all of these features, but can evolve into poorly regulated systems without pressure measurement, missing orifices and deteriorating and/or plugged water piping. Mills which have allowed clean and fresh seal water for these systems usually require little or no vacuum pump maintenance or overhauls. Those systems which recirculate seal water through cooling towers are usually in the worst shape. Basic components are needed regardless of using once through fresh water systems or recirculated systems. Seal water headers can be controlled to a reasonable pressure, then throttled at the vacuum pumps. Local throttling valves are usually ball valves. Orifices and spray nozzles should be verified with the pump manufacturers so correct flows are delivered. Local pressure gauges are necessary to allow pressure adjustments. No elaborate flow meters or other controls are required. Some mills have installed simple rotameters at each pump to monitor seal water flow. Others may have a single flowmeter to monitor seal water to the entire system.

These systems get messy when cooling towers are introduced. Most vacuum systems installed in the past 25 years have included cooling towers to provide reasonable seal water temperatures without continuous fresh water and sewer requirements. A few mills were creative and could classify seal water as "non-contact cooling water" and utilize fresh water. Where cooling towers have been used, problems have included:



Typical splash fill cooling tower for vacuum system

- Incorrect tower fill
- Lack of working separators
- Undersized separators
- Separator extraction pump problems
- Overloaded water filters due to excessive water contamination (because of separator issues)

Often, no one seems to have process ownership of these cooling tower systems. They are always outside of the paper mill machine room so are not within the normal path of operators on routine rounds. Problems associated with recirculated seal water and cooling towers are usually not noticed until serious pump problems develop and cooling towers are requiring rebuilds or replacement. The photos show splash fill within the tower indicating water contamination and a clean water system.

Serious seal water problems

Clean seal water system

Best Practices with seal water systems include the following:

- Awareness of basic seal water process and vacuum pump requirements
- Use of orifices and spray nozzles with pressure measurement and control, or means of flow measurement for each pump
- Working local pressure gauges
- Understanding of necessity for separators and extraction pump systems
- Daily or at least weekly inspection of cooling tower
- Simple seal water analysis (pH, conductivity, turbidity) and looking for changes

<u>Excess Vacuum Capacity and Reducing Operating Power</u>: Yes, paper machines often have excess vacuum capacity. It usually is not an obvious situation and most papermakers feel that this can never be a problem. Excess vacuum system capacity does not cause papermaking performance or efficiency problems. However, this problem relates to minimizing papermaking costs. There are usually opportunities to lower operating power by 10 to 20% through analysis and optimization of the vacuum system.

Sometimes these issues are identified by studying vacuum inbleed valves and their typical positions. Inbleed valves which never close are opportunities for reducing vacuum system horsepower. Other opportunities include elimination of press suction rolls, typically found on older containerboard machines and pulp dryers, and unnecessary flatboxes and uhle boxes as described earlier. Finding larger opportunities require an in-depth study of the system. The greatest improvement uncovered to date was on a 360” printing paper machine which was able to remove 1.2 megawatts from the vacuum system. This was a 40% horsepower reduction.

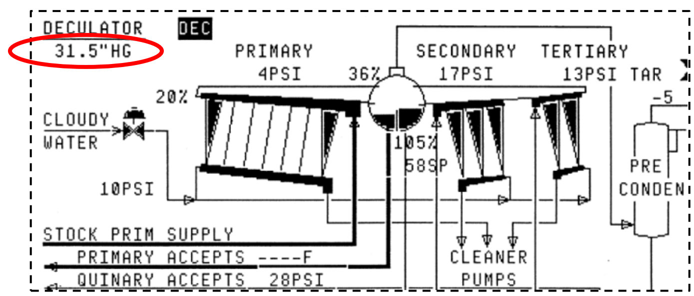
Vacuum system optimization and application of best practices usually result in cost savings. Best practices for minimizing necessary vacuum capacity and operating power include the following:

- Investigate operation with open vacuum inbleed valves
- Conduct detailed vacuum-dewatering analysis and system audit
- Remove unneeded flatboxes and uhle boxes
- Eliminate press suction rolls where possible – generally, working with roll cover shops and fabric suppliers helps accomplish this
- Monitor vacuum pump motor loads and investigate changes, up and down

MANAGEMENT BEST PRACTICES:

Training and General Vacuum System Knowledge – Although we are in a technology boom with “smart” equipment and computer control, paper mills can’t run themselves. People are still working hard to keep processes within desired operating ranges and when all isn’t perfect, they are washing down the machine to get ready for thread-up following a sheet break. Often, operators with 25 years of experience are not able to provide basic information or do not understand cause and effect within these systems. Although training should be ongoing and applied to all processes, this is a vacuum systems presentation so specific vacuum systems needs are discussed.

Vacuum systems training needs to begin with the basics of vacuum measurement. This should include understanding of the difference between inches of water and inches of mercury. Orders of magnitude need to be explained to allow operators to know that full vacuum of about 30” Hg is only equal to 15 psi. Often operators will express vacuum in pounds of vacuum.



A favorite example of a lack of understanding of vacuum measurement was with a DCS display showing Deculator vacuum of 31.5” Hg. No one in the control room seemed to be concerned that this was an impossible value.

Vacuum measurement is usually found to be as poorly executed as seal water control. Local gauges are not maintained and procedures do not exist to check and calibrate transmitters. Other issues include incorrect gauge types (vacuum vs. compound) and physical locations which are difficult or just unsafe to maintain.

Examples of training needs were described in earlier discussions about table vacuum, seal water control, cooling towers and vacuum separator systems. Best Practices for operator training include the following:

- Review and update vacuum system training and include understanding of vacuum measurement, subsystem operations (separator/pump systems, seal water, and cooling towers)
- Review vacuum gauge applications and eliminate use of compound gauges – replace inoperable gauges
- Develop improved operator inspection efforts in daily rounds

Housekeeping – There is little which is less technical in a mill than housekeeping. However, there are many examples illustrating how a clean mill generally operates better and more safely. This is truly a management and mill culture issue. Recall “The Ear Plug Theory”, which was published in a Pulp & Paper editorial ten years ago.

This suggested a correlation between the number of discarded earplugs between the paper machine and parking lot and paper mill operating efficiencies.

More earplugs = poor housekeeping = lower efficiencies

This applies to the vacuum system because generally the vacuum pumps are in the basement and/or outside the mill. Therefore, vacuum pumps are out of the normal line of sight for operators and likely never in the path of a mill tour group. Since vacuum pumps don't usually require a lot of daily attention they seem to become forgotten until serious problems arise. Housekeeping and management supporting clean mill environments usually result in more frequent interaction with systems not on the operating floor.

10" diameter vacuum line with failed rubber boot. Leak caused 5" Hg of vacuum reduction. Duct tape indicates previous attempt to fix.

Many vacuum studies have resulted in findings of basic issues which have become ignored. This can include vacuum and water leaks, bearing failures due to excess and lack of lubrication, inability to identify critical items due to excess grease slinging off the pump shafts, flooded areas due to plugged drains and lack of lighting to allow basic inspections.

Mill personnel are often apologizing when some of these relatively simple findings are discovered because this was possible when some attention was given to the equipment and system.

Housekeeping Best Practices:

- Buy more trans cans – empty cans regularly
- Clean excess grease following routine lubrication
- Clean grease and slime from handrails so people can use them safely
- Consider it unacceptable to clutter floors and catwalks
- Repair/replace broken lighting - cleaner and better lighting allows better audits

<u>Equipment Identification</u> – Coinciding with training, accurate labeling of process piping and equipment is essential. Physical identification of piping and equipment with easy to read labeling is necessary. Also, process drawings and computer schematics (DCS) need to show the same information. However, as mills age and process have become modified, this is an item which is often not completed with the project. There are a few basic Best Practices related to equipment labeling and documents.

- Labeling vacuum pumps and auxiliary equipment
- Labeling valves and blanks within the vacuum piping network and accompanying this with documented information about valve/blank positions. (Normally closed or normally open)
- Process drawings need to be current to show accurate information.
- DCS displays which accurately show processes is essential. However, this is often found to not be the case. Senior operators seem to recall which changes have been made, but as soon as a backtender is filling in all bets are off. Somehow, projects are executed but there was not time or money to update DCS graphics.
- Use of bar charts in DCS displays besides just raw data can provide quick identification of issues.

Examples of good labeling

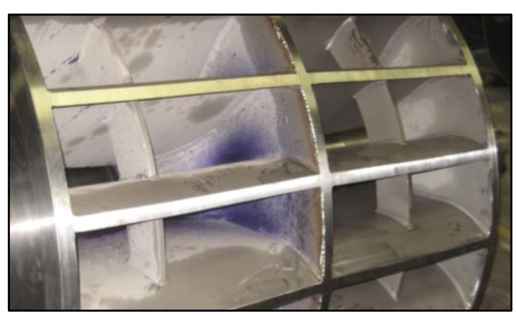
<u>Vacuum Pump Maintenance and Repairs</u> – Many people are involved in this effort, including lubrication and vibration techs, maintenance superintendent, maintenance planner and purchasing managers. Essential in-house maintenance includes routine bearing lubrication and vibration measurement and trending. Vacuum pump condition/performance can be determined by several methods, including: performance testing (easiest with smaller pumps), fiberscope inspections of pump internals, and measurement and trending of system vacuum levels and operating horsepower. This last item, trending operating data, is seldom done. Many mills will spend $50,000 to $100,000 for removal, rebuilding, shipping and reinstalling large vacuum pumps which were in good condition. Errors can exist in performance test results and analysis of fiberscope inspections. Meanwhile, no one in the mill has questioned why a pump reported at 50 – 60% of new performance had little or no change in vacuum or horsepower before or after the repair.

Some mills experience frequent bearing failures and are comfortable with bearing life of 5 – 10 years. They may not realize most liquid ring pumps are equipped with robust bearing designs which often have a design life of 15 to 20 years. Repetitive and high frequency bearing failures are often due to inaccurate machining and repair issues. Other causes of bearing failures are due to poor lubrication practices (lack of or excessive), misalignment, incorrect coupling selection, and corrosion and deterioration of bases and foundations.

As mentioned, vacuum pump bearings have long design lives. Where seal water quality is very good it is not surprising to find every pump on one paper machine to be in almost new condition after 25 years. At that point it is wise to begin a bearing replacement effort.

Vacuum pump manufacturers have OEM repair facilities or authorized service centers. There are several other machine shops which repair vacuum pumps only, and many more offering to rebuild whatever has recently broken. The OEM facilities will use original and remanufactured parts and have manufacturing drawings. Similar to rebuilds of fans and centrifugal pumps, other shops will be reverse engineering components and may have acquired some original drawings. It is worthwhile to visit these facilities before choosing where a vacuum pump is to be rebuilt. Request a disassembly report including photos. Visiting the shop during disassembly is a good choice to get a better understanding of wear and failure issues. Consider testing the pump for capacity and horsepower following the rebuild.

Two fabricated stainless steel rotors for the same pump model – right is OEM. Left side tested at 65% of new performance.



Once the pump is reinstalled, determine if the bearings were adequately lubricated during the rebuild, and if so, don't add more grease. A few mills are still relying on oil lubrication and this is easier to determine. After installation, alignment and start up, pay attention to adjusting packing during the first few weeks. Sometimes this is ignored and finally gets attention when the shaft seals are seriously leaking water, which can get into the bearings.

Maintenance and repair of vacuum pumps should include these Best Practices:

1. Understanding long bearing design lives, investigate repeated failures of specific pump bearings, or random failures as frequently as within 5 years of replacement.
2. Develop good procedures for bearing lubrication amounts and frequency. Resist excessive lubrication.
3. Develop good procedures for monitoring bearing vibration and temperature.
4. Review procedures for pump alignment.
5. Inspect pump bases and foundations for deterioration. These can be over 50 years old.
6. Consider performance testing rebuilt pumps.
7. Either performance test or fiberscope vacuum pumps at least every two years. Frequency can be longer depending on specific mill experiences. Compare motor loads and vacuum levels to performance data when evaluating if a pump is needed to be overhauled.
8. Analyze time between failures and compare entire repair cost (overhaul, removal, reinstallation, shipping) when evaluating pump repair choices.
9. Choose repair facilities after some research, comparison and even site visits.

SUMMARY

Paper machine vacuum systems are an important process for paper machines. Since these systems generally require less maintenance and attention, they become less understood. Decisions for enhancement of dewatering systems can be incorrect and the system can evolve poorly and inefficiently. Items presented should be useful to paper production and maintenance personnel. Applications of the best practices which have been presented often will require little cost. Benefits will always be measurable.

REFERENCES

1. Sweet, Doug, Retrocommissioning and Energy Efficiency, Pulp & Paper International, Nov/Dec 2015, pg 24 – 32
2. TAPPI TIP 0502-01, Paper Machine Vacuum Selection Factors, 2013
3. Sweet, Doug, A Systems Approach to Felt Conditioning, TAPPI Journal, July 1997, pg 103 – 108
4. TAPPI TIP 0420-12, Guidelines for Measurement of Vacuum Pump Air Flow, 2012
5. TAPPI TIP 0502-19, Use of Ceramics on the Forming Section: Diagnosing and Preventing Forming Fabric Wear, 2011