Electrostatic Purification Helps Pulp Mill Control Sludge and Varnish

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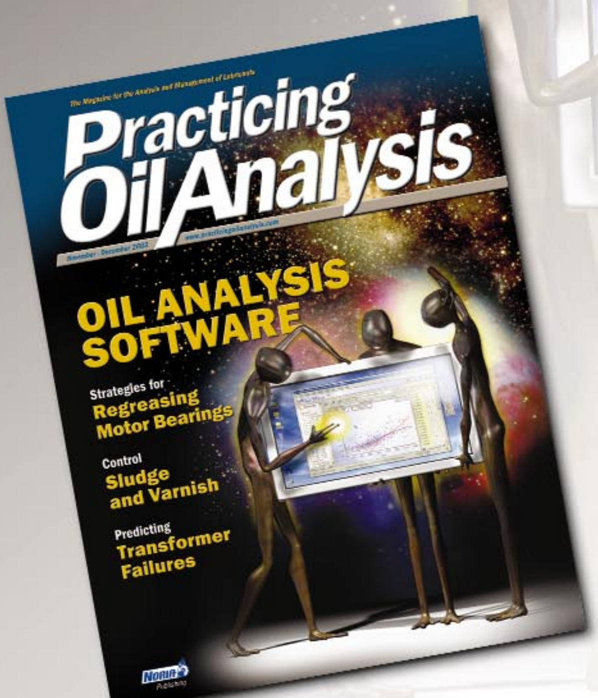

"After several years of dealing with a sludge and varnish problem in its slab presses and bale presses, Millar Western Forest Products Ltd. initiated a trial using advanced oil purification systems. The trial, which incorporated electrostatic purification, turned out to be the method of choice for long-term, cost-effective management of varnish and oxidation by-products in this mill's press environments."

ASL Electrostatic Fluid Purification Systems

Electrostatic Purification Helps Pulp Mill Control Sludge and Varnish

By David M. Bickford, ASL Technologies LLC

With hydraulic fluid ISO cleanliness levels of 14/10/7 to 15/12/10 on a main slab press, it is hard to imagine that it would be necessary to dump and replace fluid this clean. However, that is the position Millar Western Forest Products Ltd., a large Canadian forest company, found itself in at its chemi-thermo-mechanical pulp (CTMP) mill in Whitecourt, Alberta, Canada.

By developing and implementing a comprehensive oil analysis program in 1997, mill personnel had managed to reach ISO cleanliness levels seldom seen at pulp mills with similar presses. Nevertheless, mill staff still found themselves replacing this fluid due to component failures and premature oil degradation. In this case, having a first-class oil analysis and condition-based maintenance program was not enough to eliminate the system-generated varnish and oxidation by-products noted in oil test results and component inspections. After several years of dealing with the problem through complete oil drains in conjunction with reservoir cleanouts, the mill's maintenance staff elected to try two advanced oil purification systems. The first trial, started in May 2001, was on an ultrafiltration unit; the second, started in March 2002, was on an electrostatic fluid purifier. Although both systems proved effective, the electrostatic technology turned out to be the method of choice for long-term, cost-effective management of varnish and oxidation by-products in this mill's slab and bale press environments. Electrostatic purifiers installed by Millar Western have eliminated the need to dump and replace hydraulic fluid, and provided the system reliability and oil durability mill personnel were striving to achieve.

Millar Western's slab presses are high-production machines that apply 400 metric tons of force with a large vertical stamp, three or four times through each cycle.

How the Presses Work

Millar Western has three identical slab presses in its Whitecourt CTMP facility, one of which was initially targeted for the trial. The slab presses compress pulp into large, rectangular bales that are ultimately shipped out to the company's customers - paper manufacturers. Once the pulp is refined, washed and bleached, it is put through a drying process that results in a fluffy, 93 percent bone dry pulp. This dry pulp gets distributed to two storage chutes within each slab press. Each slab press is a high-production machine that applies 400 metric tons of force with a large vertical stamp, three or four times through each cycle, to compress each 225-kilogram (500-pound) bale. The cycle time to produce each bale is between 35 and 60 seconds, depending on the desired production rate, with typical hydraulic system pressures of 200 to 250 bar (2,900 to 3,600 psi).

One of Millar Western's slab presses is dedicated to a line (Line No. 1 - the press targeted for the trial) that processes 400 metric tons of pulp each day, while another slab press is dedicated to a line (Line No. 2) that processes 440 metric tons of pulp each day. The third is a swing slab press that is routed to whichever line is exceeding the production rate of the dedicated press; or, if there is a problem with a dedicated press, the swing press will maintain a reduced production rate while repairs can be performed. So, the dedicated presses typically run flat out, with 8 to 12 hours of scheduled downtime each month. Once each bale is formed by the slab press, a bale press then applies 1,500 metric tons of force to reach the exact dimensions required for wrapping, storing and shipping to the mill's customers around the world.

Varnishing occurred in the mill's slab and bale presses since their startup in 1988; however, it seemed to get significantly worse as the production capacity through each press was increased over the years.

The Root of the Problem

"Millar Western initially thought that high reservoir temperature was the root cause of the varnish problem, so a larger-capacity cooling system was added to each press," said Gerry Trodd, Millar Western's CBM supervisor. "But, despite this installation, we continued to see excessive amounts of varnish building up within the press components."

As excessive varnish continued to find its way into the press components, plant maintenance personnel were faced with the chore of completely draining the reservoir and manually scraping off as much varnish as physically possible. This was not only a time-consuming (12 to 16 hours) job for four to six people; it was dirty, messy work that required opening up the reservoir and thus increasing the risk of contamination to the fluid from external sources. In addition, when the presses were opened, it wasn't always easy to get them back into operation without complications - it could take a while to get the new oil cleaned and filtered to 5 microns and the machine back up and running.

"Although a valiant effort, this was only a temporary, band-aid solution, and one that addressed the reservoirs only, while doing nothing for the integral components and the meters upon meters of pipes and hydraulic lines within the contaminated system," Trodd said. "In an effort to come up with a better solution, we worked extensively with our lube-oil supplier, Imperial Oil, to better understand what mechanisms within the press were causing the varnish generation and what practical options were available to resolve the issue. The design and operation of the presses cause them to virtually drain and refill the 4,500-liter (1,200-gallon) reservoir with each stroke of the large press stamp. This means little to no dwell time of the hydraulic fluid within the reservoir, resulting in air entrainment. Although we now have the reservoir temperatures under control, we still have many hot spots within the hydraulic system, all of which add up to a perfect environment for microdieseling. (See Microdieseling Explained on the last page.)

"Even though the varnish problem existed, the presses remained very reliable, so getting a fix on exactly how much this issue was costing us, either in maintenance dollars or production lost, was tough," Trodd said. "The fact that the presses were required to operate 24 seven contributed to our desire to find a solution to the varnish problem; however, we had not gotten ourselves into a position where downtime was a concern," Trodd said. "And, perhaps what sets this case history apart from most is that our oil cleanliness level through this period was maintained at a ISO 14/10/7 to 15/12/10."

Each press cost millions of dollars, so replacing them was not a solution to the problem, nor was redesigning the reservoir, which would also have been a complicated and expensive solution. Because the presses were expensive and remained reliable, it was easy to justify the cost of dumping and replacing the hydraulic fluid, an easy fix compared with a complete redesign. Nevertheless, there were obvious costs associated with the loss of 4,500 liters of hydraulic fluid plus the labor involved in cleaning the reservoir and replacing the fluid. Millar Western's maintenance staff knew they could do better.

"One of the key performance indicators of our oil analysis program is our overall plant oil consumption. The long-term effects of simply dumping the 4,500 liters every time we addressed the varnish issue within each press were unacceptable in terms of the objectives we had set. The drive to meet our oil consumption goals forced us to investigate a better solution both to the immediate issue of varnish build-up and to the longer-term issue of reliable press performance," Trodd added.

The main problem with the tar and varnish occurred when one of the presses' hydraulic pumps would fail. "When a pump fails, it dumps tramp metal into the reservoir. If the tramp debris is left in the reservoir, it will make its way into the other five hydraulic pumps in the system and cause damage to them," Trodd said. Therefore it was mandatory that the reservoir be cleaned immediately if one of the six hydraulic system pumps failed. Rather than taking 8 to 10 hours to clean the tramp debris from the reservoir, the process took much longer because the varnish had to be removed at the same time. This was deemed to be an important step, because sludge and varnish are known to lodge metal and other solid particles in critical clearances such as valves, compounding the pump failure problems.

Electrostatic Purifiers Manage the Problem

Because the varnish problem was not being solved using conventional filtration methods, Millar Western began a seven-month trial with an electrostatic purifier. The trial was monitored through regular oil analysis performed by both Imperial Oil's Sarnia Research Center, and the manufacturer of the purifier.

In March 2002, an electrostatic filtration system was connected in a kidney loop configuration to the slab press reservoir. The oil type in use was NUTO H 68, a conventional mineral-based antiwear hydraulic fluid. The electrostatic system was configured with a flow rate of 40 gallons per hour, giving a single pass time for the whole system volume of approximately 112 hours, or a little less than five days. This low flow rate is common in electro-static systems and is required due to the forces at work inside the electrostatic chamber.

The system operates on the principles of electrostatics and electromagnetism to trap and hold all particulate carried by the target fluid, regardless of particulate size. Using high DC voltage with almost no current, the fluid to be cleaned is forced via a pump through a chamber, where it then flows through a series of oppositely charged perforated plates. Submicron particulate matter suspended in the fluid is charged positively or negatively. Coulomb forces reject the charged particulate away from the plate with a similar charge to the particle, while electrostatic forces draw particles toward the plates with opposite polarity.

Permanent ceramic magnets are suspended in the path of the oncoming particulate and the resultant magnetic flux field creates turbulence in the oil. Located just above the magnetic field, the positive plate has a clockwise revolving corona force field, which interacts with the magnetic force field, creating further turbulence, causing the particulate to become trapped, suspended in the two force fields, while the host fluid flows around it. (See Electrostatic Fluid Purification Principles Explained on page 24 for more detail.)

Baseline analysis by the research department of Imperial Oil Products, dated March 27, included the comment:

> *"The sample of used NUTO H 68 submitted contained a moderate amount of sediment. This elevated sediment may contribute to linework blockages especially where close tolerances occur, it is abrasive in nature and will contribute to wear. Purification may aid in reducing the sediment content. Foam tendency and stability were also considered to be very poor. Excessive foaming affects the lubricating properties of the oil and can accelerate oxidation due to the intensive mixing with the air. It can also lead to oil loss, resulting in higher operating temperatures, cavitation and wear. All other inspections were considered satisfactory."*

Additionally, a 0.8 micron millipore patch test and laser particle count were performed prior to the start of the electrostatic filtration trial. The patch test scanned at a visible contaminant residue (VCR) number of 14.8. This number would be roughly 99 for a black sample, and near zero for a perfectly clear sample. The ISO cleanliness level was 17/16/14. Initial particle concentration is shown in Table 1.

After 12 hours of electrostatic filtration, the ISO cleanliness level was 15/12/10, the patch number went down to 9.7 (Table 1).

Two months later, another sample was tested by Imperial Oil, with the noted sediment considered moderate. The ISO cleanliness level was down to 14/10/7, significantly lower than before the start of the trial (Table 1).

Both the press and the electrostatic filtration system continued to operate 24 hours a day, seven days a week through the summer. Periodic oil analyses were performed and indicated that the ISO cleanliness levels remained around 14/10/7, while

Table 1. Oil Analysis Results

	Beginning of trial	12 hours later	Two months later	End of trial
ISO Cleanliness Level				
	17/16/14	15/12/10	14/10/7	13/10/7
Particle Concentration				
> 2 μm	1,220	269	106	51
> 5 μm	394	38	7	5
> 15 μm	92	5	1	1
> 25 μm	48	1	1	0
> 50 μm	21	0.1	0	0
>100 μm	15	0	0	0

Table 2

Component	Pretrial Readings	Post-trial Readings	Current Readings (September 2003)
Calcium	32 ppm	28.7 ppm	33.1 ppm
Iron	1 ppm	1.9 ppm	2.3 ppm
Phosphorus	342 ppm	339 ppm	345 ppm
Zinc	383 ppm	365 ppm	391 ppm

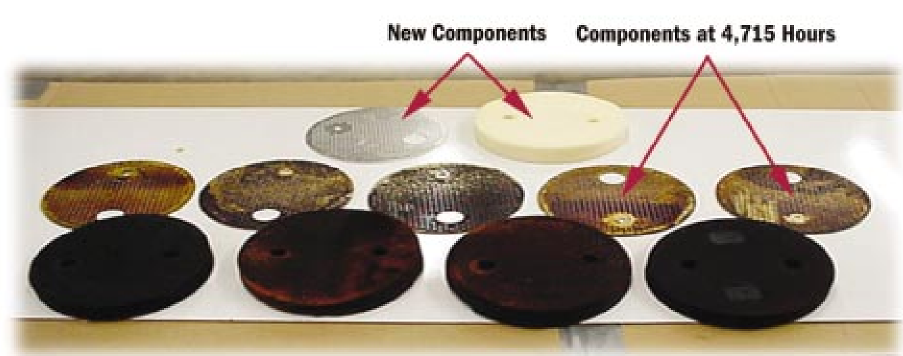

Figure 1. New and Used Electrostatic Cell Components

Electrostatic Fluid Purification Principles Explained

At a basic level, the principles of electrostatic filtration are simple; any two particles or surfaces with opposing electrical charges will have a mutual attraction. In an oil-lubricated system, many of the common contaminants such as dirt particles and wear debris are either polarized (carry a small electrical charge), or can be easily polarized using a high voltage field. As such, they can be removed with an appropriately charged metal plate, or other electric field gradient.

However, the strength of electrostatic purifiers lies not in its ability to remove solid particles, often referred to as "hard" particles but in removing unwanted "soft" particles, such as oil degradation by-products. Left unchecked, it is these degradation by-products that plate out on critical machine surfaces like valves, pipe work, bearings and coolers, causing varnish and sludge build-up.

Electrostatic off-line fluid filtration is gaining in popularity and use as knowledge and experience with these systems spreads. Formerly considered a high-end capital expenditure, electrostatic filtration systems have now bridged the gap between price and performance. While these off-line systems cannot take the place of in-line, high-pressure mechanical filters; used in conjunction with conventional filters, they can be very effective in helping to control hard and soft particles, as well as sludge and varnish build-up. This is particularly true where high-pressure hydraulic systems and other circulating systems, where compressive heating and other stressing factors make oil degradation a real problem.

Electrostatic filtration is not a "one pass" technology. To achieve and maintain the lowest ISO cleanliness levels possible, the reservoir's entire contents must pass through the system about once every 24 hours. Due to the nature of the forces at work inside the electrostatic cell, flow rates of these systems are fairly low. On typical hydraulic systems, flow rates ranging from 30 gallons per hour (GPH) to 80 GPH are common. Nevertheless, even at these comparatively low flow rates, electrostatic filtration can be an effective proactive solution to maintaining optimal fluid condition. The following discussion of electrostatic separation is based on the design advanced by ASL Technologies. The design and operating principle by other manufacturers of charge particle and electrostatic separators can vary considerably.

A Trip Through the Electrostatic Cell

Fluid to be cleaned first enters the cell at the bottom (Figure 2), where it collects and fills in the expansion area so that the entire cross-sectional area of the cell is exposed to the fluid. As the force of the pump moves the contaminated fluid upward, it immediately encounters the first perforated metal plate, which has a negative charge. Passing through this plate, some particles become negatively charged due to an inductive effect, and are repelled upward by coulomb forces. Many of these charged particles then remain in the pores of the filter media immediately above the plate. Likewise, any particle entering the cell that already has a negative charge is similarly repelled by the first plate, and may also become trapped.

Any particles having a positive charge are attracted by and cling to the negatively charged particles, causing the agglomeration of smaller particles, where they may also be trapped within the pours of the media which becomes the "straws" into which the particulate find a home. Contaminants having no charge also pass through the plate and may or may not accept a charge depending on their characteristics. These particles will also be repelled by the coulomb force, and may become lodged within the straws of the foam.

Smaller particles that are too small and do not become lodged within the foam are forced upward to the next plate, which also carries a negative charge. When the particles pass through this second plate, most, if not all remaining particles are now carrying a negative charge, if they are not already embedded within the fibers of the foam media.

Two layers of foam media now separate the particulate from the third plate, which unlike the first two plates carries a positive charge. The remaining negatively charged particles are repelled by the negative plate toward the positive plate. Permanent magnets that create a toroidal flux field (Figure 3) acting in directions D1 and D2 are buried between the two foam layers. Due to the intense localized electrical field, a corona (Figure 3) forms around the positive plate, creating a force field (D3), which acts in a counterclockwise direction. As Figure 4 shows, the toroidal flux field aids the corona at some places and opposes it in other places, creating a turbulence of particles suspended in the fluid.

Already confined within the straws of the foam, particles remain in constant motion, more or less trapped in the resultant force field established by the interaction of the flux and corona. The different effects at different locations in the force fields tend to create greater random agitation. However, because the particles are already confined within the straws, this agitation causes them to become even more imbedded within the foam.

For any contaminants that do pass through and encounter the positive plate, an effect similar to the effect of the negative plate takes place. Positively charged contaminants that remain in the fluid are repelled by the positive charge on this plate and seek negative particles, eventually becoming large enough to become trapped in the foam.

As the fluid advances through the filter, any contaminants remaining in the fluid go through the same process three more times, until finally receiving a negative charge before passing out of the cell and returning to the reservoir. As Figure 3 shows, the density of the foam increases for the last two corona/flux field interactions. Depending on contaminant ingress rates, three to five cycles through the cell will, 90 percent of the time,

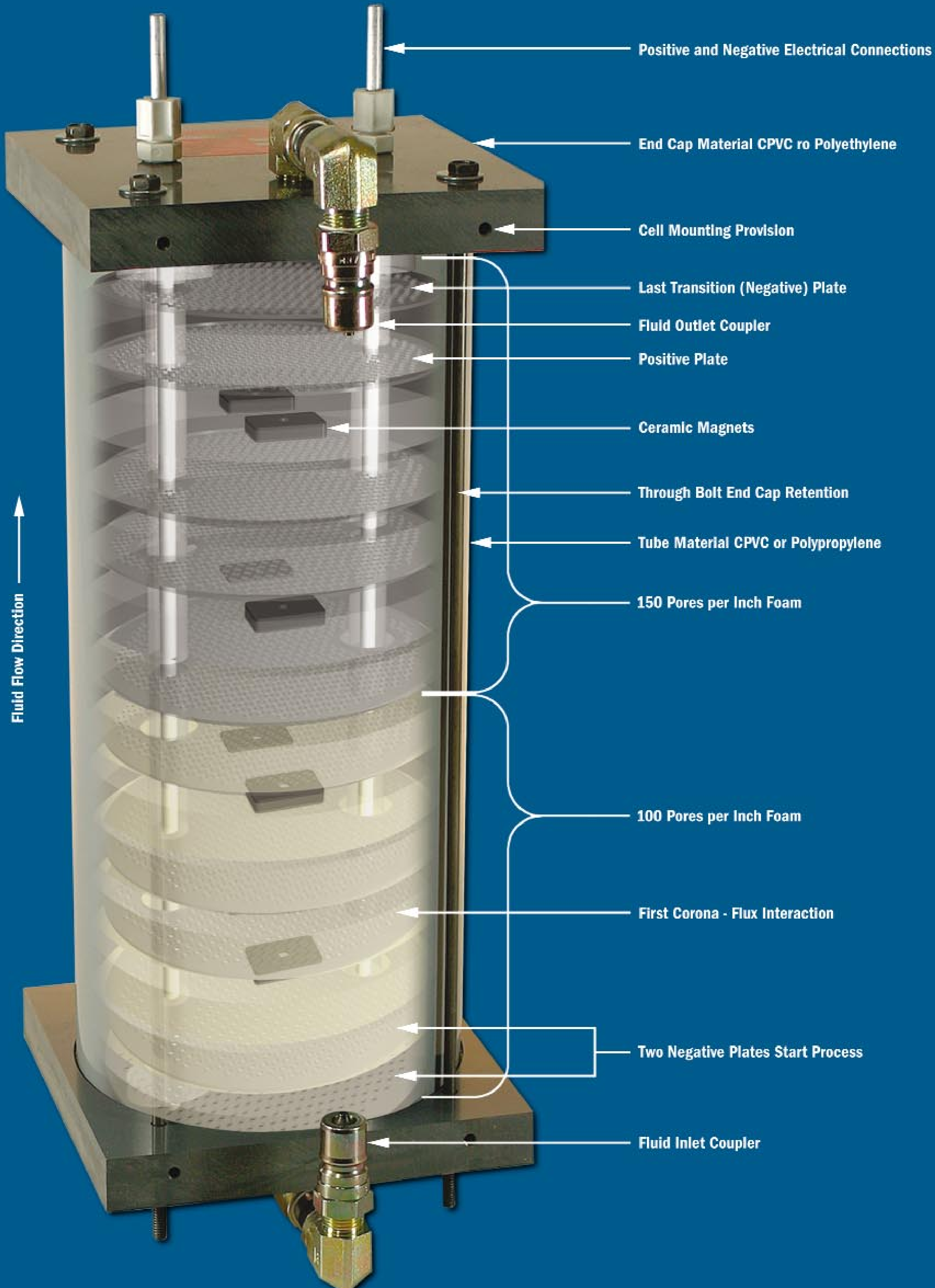

Figure 2. Electrostatic Cell Construction

The electrostatic chamber or cell is a cylindrical shell, or tube, capped with square end blocks. The necessary provisions for fluid inlet, outlet, mounting and electrical connections are located in the square end blocks.

yield an ISO cleanliness level of at least 12/10/7. In other cases, an ISO cleanliness level of 10/7/0 is achieved.

Over time, just like any filter the foam becomes plugged. However, unlike most filters, particles can be removed simply by back flushing the unit. The need for a back flush is sensed automatically by the unit, based on microamps (current) sensed by the high voltage DC power supply, causing a warning light to be illuminated on the instrument control panel. When power is removed from the cell, any contaminants held in the electrostatic force field are released and the cell can be back flushed with clean, dry shop air (reduced to 10psi). This removes most of the particulate and about 1.5 gallons of oil for disposal. The cell is then returned to service. Over time (approximately one year at typical ingression levels) back flushing is no longer effective and the cell is replaced. The spent cell is returned to the factory for reconditioning.

Fail safes include interlocks that stop the pump in the event of power supply and other related system failures and a trip feature whereby the system will continue to operate if the "back-flush" warning light is ignored, until a predetermined set-point is reached, at which time the system shuts down, illuminating a “low (cell) voltage” light. Based on 24 hours a day, seven days a week operation, the cost of cell renewal is less than 4 cents per operating hour.

Electrostatic Cell Construction

The electrostatic chamber or cell, shown in Figure 2, is a cylindrical shell, or tube, capped with square end blocks. The necessary provisions for fluid inlet, outlet, mounting and electrical connections are located in the square end blocks.

The electrostatic cellreveals many design and manufacturing considerations. The positive and negative electrical connections, sealed by plastic compression fittings, are exposed at the top to facilitate connection to a specially designed high-voltage DC power source via a “spark plug” terminal and rubber boot having enough length and insulating capability to shield the connections from arcing or injury.

The end caps are constructed of either chlorinated poly vinyl chloride (CPVC), for use with the more common types of hydraulic, turbine and lubricating oils, or polyethylene when filtration of phosphate ester fluids is desired. These materials are relatively inexpensive, easily machined and have little difficulty withstanding temperature ranges typically seen in most systems. To seal the end caps to the tube, O-ring groves are machined into the caps.

Commercial quick-disconnect couplings are used to minimize external contaminant ingression and ease installation and system maintainability. Threaded holes on both sides of the end caps provide secure mounting points for the electrostatic cell. Simple threaded through bolts retain the end caps to the tube, and are affixed with positive locking nuts. Like the end cap, the tube is made of PVC, or polypropylene when phosphate ester fluids are filtered.

The electrostatic cell depicted in Figure 2 is approximately 20 inches tall, with 7.25-inch square end caps, and weighs approximately 16 pounds dry. A single cell can operate at flow rates of approximately 40 GPH. Using the preferred formula of one reservoir cycle every 24 hours, a single cell system, with a 40 GPH pump, can support a reservoir of approximately 1,000 gallons or less. The unit is scalable such that on larger systems requiring higher flow rates, multiple cells can be connected in parallel. A reservoir of roughly 2,000 gallon capacity would require a single pump and motor of 80 GPH capacity and two of the cells pictured in Figure 1. Depending on plumbing complexity, multiple cells can effectively filter reservoirs of unlimited capacity. The largest such system built to date with this unit is a 24 cell 1,000 GPH system, supporting a 22,000 gallon turbine oil reservoir.

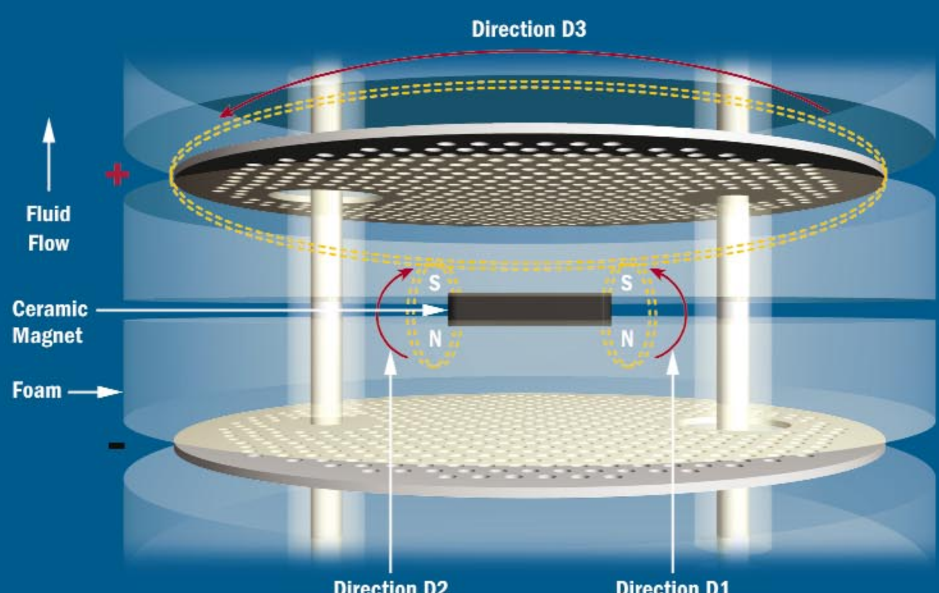

Figure 3

Permanent ceramic magnets suspended between the negative and positive plates form a toroidal flux field, acting in directions D1 and D2 (relative to fluid flow). This toroidal flux field interacts with the counterclockwise (D3) corona formed around the positive plate. As particles suspended in the fluid enter the resultant force field, the turbulence created by the interaction of these force fields causes random agitation of the particulate, causing it to become embedded within the micropores of the foam.

Different effects at different locations in the force fields tend to create greater random agitation, as the particles are accelerated at some places and resisted at others. This not only makes entrapment of submicronic sludge, varnish and oxidation by-products achievable, but also effectively doubles the holding capacity of the electrostatic cell. A microampmeter connected to the cell shows the relative amount of power required to hold particulate in suspension.

the millipore patch fluctuated, sometimes lighter, sometimes darker. Differences in the amount of oil agitation at the time of sampling, oil top-off times and dates may account for some of the fluctuation.

Approaching the end of the long-term test period, the ISO code was still around 13/10/7 (Table 1).

Imperial Oil's final report, dated October 28, 2002, showed no (0 percent) sediment volume. The foam tendency and stability of this last sample was still considered poor; however, this tendency was improved from previous samples. All other inspections were considered satisfactory per the lab report.

Along the way, acid number (AN) went from 0.60 to 0.49. Results for calcium, iron, phosphorus and zinc (Table 2), indicated no significant change in additive concentrations.

In this long-term test, the electrostatic filtration system operated 6,000 continuous hours without maintenance or operator intervention. Designed to operate for up to 8,800 hours before electrostatic cell remanufacture, this particular cell was torn down to show interested parties just "where the sludge and varnish went," as well as discern the remaining life of the electrostatic cell. Figure 1 shows electrostatic cell components that were removed from the test cell alongside new components. Based on thousands of electrostatic cell rebuilds, it was determined that this cell had about 30 percent life remaining.

Further evidence that the electrostatic filtration system is working came in September 2003 when, after 18 months of nearly continuous operation, the oil analysis results for the slab press supported a stable additive pack. In addition to the information provided in Table 2, the results also indicated an AN of 0.46 and viscosity of 67.1 cSt. The ISO cleanliness level remained 13/10/7. As expected, foam tendency and stability remained poor but stable.

The oil samples pictured in Figure 4 also verify that the varnish problem is being effectively managed. The image on the left is the oil sample that was taken 12 hours after the electrostatic purification system was installed. The oil sample on the right was taken in September 2003. These samples clearly show there has been no increase in suspended solids since the trial began 18 months earlier. If anything, a slight reduction in suspended solids is visible.

Reservoir Dumping and Cleaning are Eliminated

With the varnish and oxidation by-product issues being effectively managed, the company purchased additional units for its two remaining slab presses and its two bale presses. Since the installation of the electrostatic purifiers, it hasn't been necessary for Millar Western to change the hydraulic fluid in any of its presses. This means the initial unit has been operating for about a year and a half without a fluid change, and the other four presses have been operating for more than six months without one. "Right now, we are in a very good position to meet our 2003 goal for annual oil consumption, which is targeted at a mere 30,000 liters. This is an ambitious target, and without the varnish management system in place on our five presses, we'd be unlikely to make it. It would take only one unscheduled press oil change to put us over the line," Trodd said.

According to Trodd, each electrostatic unit would easily pay for itself by averting just one oil change and reservoir cleanout. Because the units were installed onto each press in an "as found" condition, the payback will be even quicker. "The test unit has already paid for itself and the other remaining units will, too, within the next 12 months," noted Trodd. Avoiding reservoir cleaning, and reducing oil consumption and disposal costs will save almost $7,500 (US) with every avoided oil change. This figure does not include savings associated with reduced production losses. "At this point, it looks like each unit's annual maintenance cost will be limited to two water-removing element replacements and one cell replacement per press. This totals about $400 (US) per press," said Peter De Boer, Millar Western's finishing line specialist. Another added bonus is the unit's trouble-free operation, said De Boer. "We are very busy here keeping things running smoothly, so part of what we were after in a unit was to be able to basically install it, start it up and forget about it. Unit alarms have been nil to rare so far; we have built an annual PM (preventive maintenance) prompt into our CMMS (computerized maintenance management system) to remind us to change the cell every 12 months of operation."

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Electrostatic Is Not For Everyone

While the electrostatic purifiers have been a good solution for Millar Western's varnish problem, Trodd warned that they are likely not to be the solution for everyone. For similar applications where contamination is a problem, along with varnish and oxidation by-products, the technology might not garner the same results; or it might need to be used in conjunction with other filters. The ultrafiltration unit trial leading up to the electrostatic trial also produced some amazing results where system cleaning was very quick; within two short months the varnish issue had been resolved to a manageable level.

"Because we maintain such a good ISO cleanliness level, which means time is on our side, and because we have no contamination issues other than the varnish and oxidation by-products, the electrostatic fluid purification system turned out to be our best, most cost-effective, long-term solution," Trodd said. "However, our ISO numbers are a bit unusual for a pulp mill with these press types; a site-specific trial would be needed to determine the best tool for other operations." **POA**

Editor's Note

The author and *Practicing Oil Analysis* editors would like to thank Gerry Trodd of Millar Western for his considerable contribution to this article.

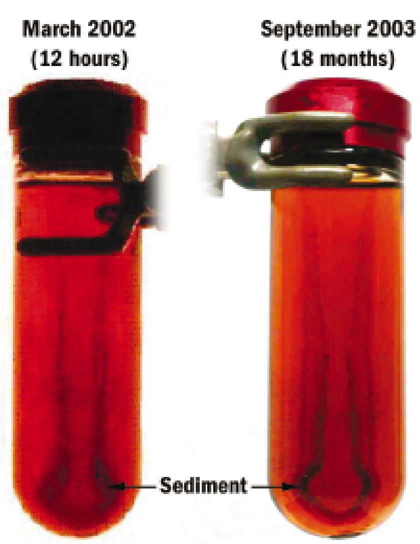

Figure 4. Ultracentrifuge Images from Slab Press

Microdieseling Explained

In systems where excess air contamination is commonplace, such as in this example, microdieseling often results. Just like oxidation, microdieseling results in oil degradation along with sludge and varnish buildup. However, microdieseling is a distinctly different chemical process than oxidation - here's how it works:

Any entrained air bubble in a system that is drawn into the suction side of the pump will be compressed. As anyone who has used a hand-operated bicycle pump will know, compressing air or any gas causes an increase in temperature: the change in temperature with pressure change is governed by Boyle's Law. According to this fundamental law of physics, compressing a gas from atmospheric pressure (the reservoir) to 2,000 psi or more (the discharge side of a high-pressure pump) will result in an increase in temperature from perhaps 100°F to more than 1,800°F, enough to turn any oil into carbon particles similar to soot - the result of burning diesel fuel at elevated temperatures. While this extreme temperature is found only in a localized area around the compressed gas bubble, over time, a significant degree of oil degradation can occur. In rolling contacts such as large rolling element bearings, where elastohydrodynamic lubrication is the norm, the situation can be even more severe with instantaneous pressures of hundreds of thousands psi.

In addition to carbon, other thermal degradation by-products are also formed. These are often termed "carbon and oxide insolubles." Over time, these by-products are deposited on the machine's surfaces, pipes and reservoir. These by-products ultimately cure into varnish and sludge.

Boyle's Ideal Gas Law

Zone	Pressure	Temperature
A	Atmospheric (Pump Inlet)	100°F
F	1,000 psi	1,410°F
H	2,000 psi	1,820°F
I	3,000 psi	2,100°F

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