



Steam Turbine Oil Challenges

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Abstract: As the appetite for electricity by modern society continues to grow, so does the desire of power plant managers to increase the reliability of their plants. The main piece of equipment used by power plants to produce electricity is the turbine; if it does not run, the plant does not produce electricity. The most common types of turbines used in power plants are gas turbines and steam turbines. Aside from turbine blade failures, the most common turbine reliability issues are bearing and control system failures, which often can be traced back to lubrication-related issues. Therefore, a turbine lubrication reliability program should be an integral part of any power plant maintenance program. In recent years, there has been significant attention given to varnish formation in power turbine lubricating systems. This paper will focus on varnish and other problems seen in steam turbines and will offer suggestions for how operators can overcome them.

Keywords: Varnish, sludge, foam, emulsion, entrained air, coalescence, demulsibility, hydrolysis, hydrotreating, interfacial tension, turbine

Introduction

To satisfy the ever-increasing demands for electricity, all power plant operators are interested in improving the output and reliability of their plants. They accomplish this primarily by ensuring that the power-generating turbine operates as frequently and efficiently as possible. Many of the issues that result in turbine downtime are lubricant-related, making it imperative that power plant management and maintenance groups work together to develop a turbine lubrication reliability program for their plants. Of the different types of turbines used for electricity production, steam turbines are among the most common. While



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there are similarities between the different turbine types and the lubricants used to lubricate them, there are specific differences. A steam turbine reliability program should be multifaceted, including functions such as lubricant selection, lubricant condition monitoring, lubricant storage and lubricant supplier service. Recent evidence from field performance and research studies suggest that it is possible to overcome many steam turbine lubrication issues through selection of a well-formulated turbine lubricant, accompanied by an entire program to ensure successful service of the lubricant.

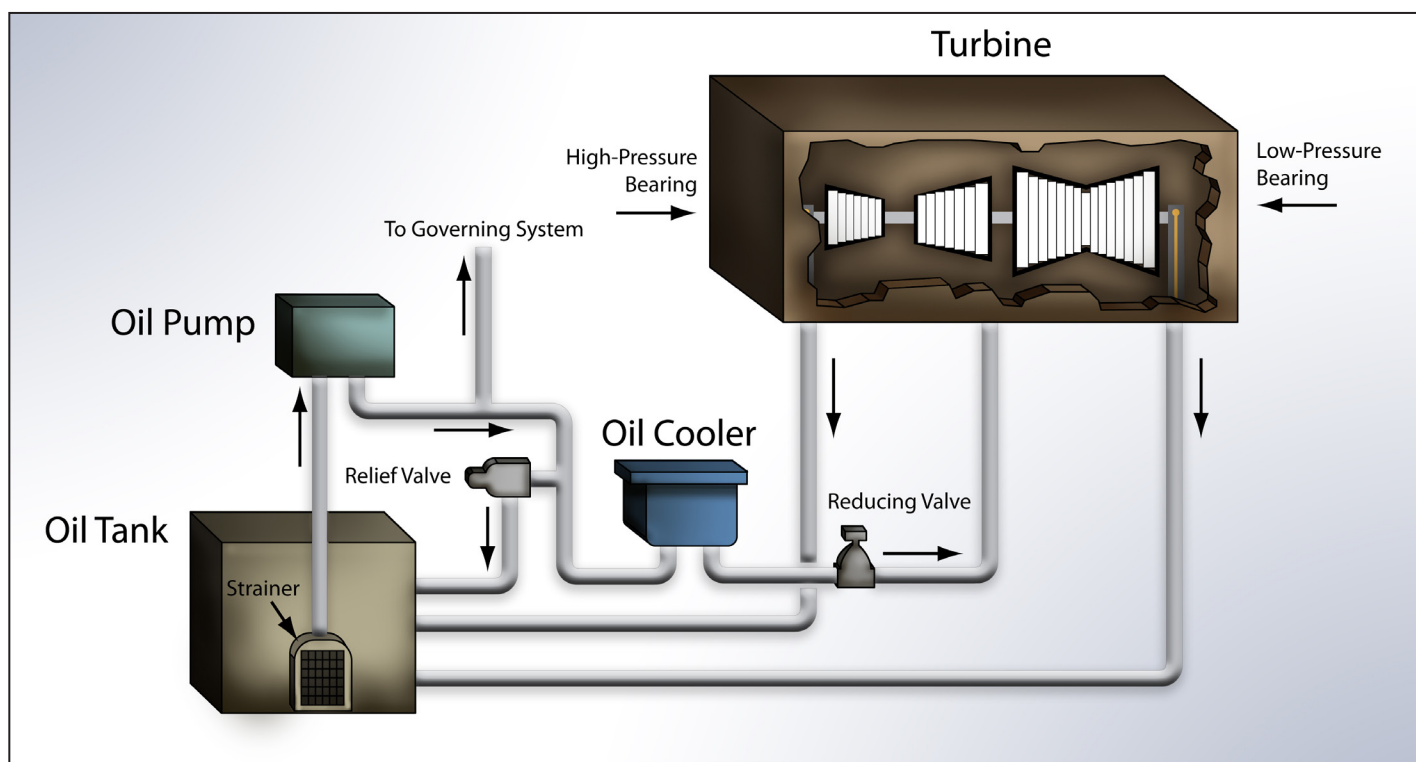
Background

In simple terms, a power turbine is a device that converts rotational energy into electrical energy. The rotational energy comes from various sources from which each type of turbine derives its name. Common names include steam turbines, gas turbines, wind turbines and hydro turbines. This paper is dedicated to steam turbines. As the name would suggest, water is heated by various means, such as burning coal or through nuclear reactions, until it becomes water vapor, or steam. The steam travels through blades attached to a shaft, thus causing the shaft to turn. The rotating turbine transfers the rotational energy to a generator that produces electricity.

For the turbine shaft to move freely, it rides upon several lubricant-filled bearings. These bearings are usually simple bearings into which the lubricating oil is pumped under high pressures. The oil lubricates the bearing through hydrodynamic lubrication. The bearings and the shaft are separated by a pressurized film of oil to prevent any metal-to-metal contact.

Figure 1 is a simple illustration of the general components and travel route of turbine oil in a steam turbine lubrication system. Along with providing lubrication to the shaft bearings, the lubricant also lubricates the oil pump, and in some systems is used as a turbine control fluid in the hydraulic governing system. Many steam turbines have an isolated governing system that contains its own fluid. In order to ensure that the high-pressure lubricant is properly supplied to the bearings, it is pumped from an oil tank (reservoir), through an elaborate system of flow control valves, an oil cooler, through the bearing, and finally back to the oil tank. The oil is constantly agitated as it circulates through the system. This agitation is important to note, as it provides both benefits and challenges for the oil during its lifetime in the turbine.

Figure 1



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Lubricant formulation

In its simplest form, a lubricant can be described as two major components: base fluid and additives. As compared to other lubricant formulations, such as engine oil, turbine oil formulations are considered rather simple. Table 1 provides a summary of common turbine oil components. For example, engine oil formulas often contain as much as 10 to 20 percent additives, while most turbine oils will generally contain 0.5 to 1.5 percent additives. The term “additive” is a broad term for various components added to the base fluid to provide specific performance benefits while the lubricant is in service. Maximum turbine oil performance provides optimum turbine performance. If the wrong turbine oil is selected, the turbine operator can experience a variety of problems. More details will be supplied on what to look for in steam turbine oil formulations later, but first it is important to consider the problems steam turbine operators experience.

Table 1 – Common Steam Turbine Oil Components

Ingredient	Description
Base Fluids	
API Group I Mineral Oil	Solvent-refined base fluid derived from refined crude oil
API Group II Mineral Oil	Hydrotreated fluid derived from crude oil (most common)
Synthetic	Synthesized fluids such as Group III Mineral Oil & PAO
Additives	
R & O	Provides rust & oxidation inhibition properties to base fluid
Anti-Wear (AW)	Reduces wear (only used in gear pump fed turbines)
Extreme Pressure (EP)	Is a synonym to AW in turbine formulations
Pour Point Depressant (PPD)	Improves low-temperature performance
Foam Inhibitor	Reduces foam and entrained air
Demulsifier	Enhances water separation properties

Steam Turbine Issues

Since the late 1880s, the oils used to lubricate steam turbines seemed to provide reliable performance with few issues. The issues that did occur were generally very predictable and were often caused by either poor maintenance practices or overextending the life of the oil. In recent years, this trend has seemed to change. Why? In the late 1990s, shifts were made in both operating conditions and in steam turbine oil formulations that began to cause a variety of problems for steam turbine operators. Operators, test laboratories and the lubricant industry have conducted significant research and most have concluded that the cause of the problems is the increased use of API Group II base oils in turbine oil formulations combined with increased use of steam turbine peaking operation.

The highest profile problems are:

- Entrained air and foam
- Loss of demulsibility
- Formation of sludge and varnish

Entrained air and foam

The difference between foam and entrained gas (usually air) in turbine oil is difficult to describe. A “beer analogy” can be used as a visualization aid to describe each of these phenomena. When beer is poured into a glass, there are two main observations that can be made. One, there is a bubbly head floating on top of the beer surface, and two, there are gas bubbles in the beer. The head on top is an example of foam, while the bubbles within the beer’s body are an example of an entrained gas. The only problem with this analogy is that the foam on the beer is a good thing, while foam on turbine oil is not. The question is: How do gases get into the oil in the first place?

As mentioned previously, steam turbine lubricant circulates through an elaborate system of pumps, pipes and bearings. During use, the oil moves from areas of high pressure to low pressure, flows and splashes through twists and turns in the turbine piping, and temporarily lies almost static in the oil tank. There are many opportunities to agitate gases into the oil. If there is no opportunity for gas to escape from the oil, it becomes entrained. When the oil reaches low agitation areas, such as the oil tank, the buoyancy of the gas bubbles allows them to rise to the oil surface where they can be released. Unfortunately, steam turbine operators often notice that instead of being released, the bubbles float on the surface of the oil as foam. When either foam or entrained air develops in steam turbine oil, it can result in catastrophic effects on the turbine oil, turbine bearings and hydraulic-controlled governing systems.

The lubricant’s primary job is to minimize wear by lubricating the moving parts in the steam turbine. Gases are not very efficient lubricants. They do not possess the proper film strength to keep the moving parts from rubbing together. Besides providing wear-reducing properties, oils have secondary purposes, such as heat transfer, corrosion protection and contamination transportation. Entrained gases can negatively impact these properties of the lubricant as well. The most common gas present in steam turbine oil

is air. Nitrogen is the highest concentration gaseous component of the air, but oxygen is the most damaging component. Oxygen reacts with the base fluid and breaks it down through a process known as oxidation. The more oxygen there is in the oil to cause oxidation, the more the oil will be degraded and its lifespan reduced.

Loss of demulsibility

Another gaseous component present in air that can be as damaging as oxygen is water vapor, which can be drawn into the turbine oil where it can condense and collect over time. This is generally a very slow route of water ingress into a steam turbine. The more rapid routes are through cooling bundle leaks and steam leaks through bearing seals. Regardless of what route water finds its way into steam turbine oil, it is a very damaging contaminant.

Water exists in three forms in industrial turbines: free water, dissolved water and emulsion. Free water is water that separates from the turbine oil and collects in pools in the low areas of the turbine and of the oil reservoir. Free water is the easiest form of water to remove from a turbine because it is present as a separate layer below the turbine oil. Dissolved water is solubilized into the oil and cannot be easily separated. Water and oil usually do not mix, so the concentration of dissolved water in new oil is rather low. Emulsion is a stable, milky mixture of oil and water that is difficult to separate. It differs from dissolved water in that it is almost a gel-like dispersion of water droplets within the oil. Although not easily removed from the oil, it is much easier to remove than dissolved water. Water in any of these three forms can result in problems for the turbine and the turbine oil that could result in reduced lubricant life, shorter equipment life and mechanical control problems. Table 2 provides a list of these problems and a brief description of each.

Table 2 – Turbine & Turbine Oil Problems Caused by Water Contamination

Problem	Description
Hydrogen-induced fractures (aka embrittlement or blistering)	Water is attracted to microscopic fatigue cracks by capillary action. Water breaks down and liberates atomic hydrogen and causes further crack propagation and fracture. Risk posed by both free and dissolved water.
Corrosion (aka rusting)	Free and dissolved water both result in increased corrosive potential of acids, which leads to etched and pitted surfaces and – in worst cases – the formation of abrasive iron oxides that can break off and accelerate wear.
Oxidation	Elevated temperatures in the presence of oxygen lead to degradation of the lubricant. When water and metal particles are present, antioxidants in the lubricant are consumed even faster. Oxidation leads to corrosion, sludge, varnish and impaired oil flow.
Additive depletion	Water depletes or diminishes the performance of lubricant additives, including antioxidants, AW, EP, rust inhibitors, dispersants, detergents, and demulsifying agents. Water hydrolyzes, agglomerates, washes out or transforms additives, and sometimes results in the formation of acids or sludge puddles on sump floors.
Oil flow restrictions	Water is highly polar and can attach to the oil various impurities that are also polar, e.g., oxides, spent additives, particles, carbon fines and resin. These attachments can form sludge balls and/or emulsions. When sludge balls accumulate in orifices, feed lines or filters, they can impede flow and cause lubricant starvation – ultimately leading to failure.
Aeration & foam	Water lowers oil’s interfacial tension, which can cripple its air-handling ability, leading to aeration and foam. Air weakens oil films, increases heat, induces oxidation, causes cavitation, and interferes with oil flow.
Impaired film strength	Bearings depend upon oil viscosity to provide critical clearance under a load. Water globules pulled into a bearing load zone reduce surface clearance and result in bumping or rubbing of opposing surfaces. This should never occur in hydrodynamic applications such as turbine main bearings. Water can flash or explode into superheated steam in bearing load zones, which can sharply disrupt oil films and could fracture surfaces.
Microbial contamination	Water promotes the growth of microorganisms such as fungi and bacteria, which produce corrosive waste byproducts and can form – over time – thick biomass suspensions that plug filters and interfere with oil flow.
Water washing	Pressurized water sprays can wash additives out of a lubricant zone. Lubricant density is lower than that of water, and too much free water can displace lubricant if allowed to accumulate. It also can cause impaired film strength.

Adapted from sources 1 & 5

To manage the many problems that water contamination can cause in power generation turbines, operators have adopted a variety of techniques. One of the often-overlooked solutions is lubricant selection. Many operators assume, "Oil's oil, what difference will the oil make? Oil and water don't mix anyway." Unfortunately, these same people often discover that this statement is untrue. The various techniques they employ to remove water from in-service oil meet with limited (if any) success. The reason seems to be that the affinity (attraction) of the oil to water has changed. Field evidence is mounting that suggests turbine oil selection may play a key role in the success of water removal techniques.

So, why does the affinity of turbine oil for water change during service? Water is considered a polar compound. There is a general rule in chemistry that states, "Like dissolves like." This implies that water is easier to dissolve in other polar compounds. It turns out that oil is a complex mixture of compounds made up of various hydrocarbons that are nonpolar compounds. Scientifically, this is why oil and water would not mix. Yet, turbine operators have had problems removing water from in-service turbine oils, indicating a change in either the water or the oil. Did the water become less polar, or did the oil become more polar? Under normal conditions, it is nearly impossible to make water nonpolar, so it must mean that oil becomes polar. A polarity shift mechanism occurs within a turbine while it is in-service that results in increased turbine oil polarity. This change in polarity increases the amount of water that can be dissolved into the oil.

The chemical reactions that cause this change in the oil are complex, but the process can be described in a simple four-step polarity shift mechanism that results in the polarity increase of the turbine oil:

- **Step 1:** Infiltration
- **Step 2:** Catalysis (galvanic reactions)
- **Step 3:** Oxidation & hydrolysis
- **Step 4:** Emulsification

Formation of varnish and sludge

Inlet steam temperatures can be in the range of 420-550°F (216-288°C). Some of this temperature is transmitted to the turbine main bearings, producing the perfect conditions for accelerated deterioration of turbine oil, especially when contaminants are introduced into the oil. When steam turbine oil is exposed to entrained gases, water contamination and elevated temperatures for extended time intervals, it causes thermal breakdown, oxidation and hydrolysis of the oil that ultimately results in advanced forms of lubricant degradation called sludge and varnish. Certain additives – called antioxidants or oxidation inhibitors – are included in steam turbine oil formulations to help improve oxidation stability. Unfortunately, the use of improper antioxidants has also been shown to contribute to sludge and varnish formation in steam turbines.

The oxidation mechanism for lubricants has been well documented. Oxidation is the reaction of lubricant base stock with oxygen, which results in oxidation mechanisms leading to degradation byproducts forming in the lubricant. Following is a simplified depiction of this process.

Oxidation Process

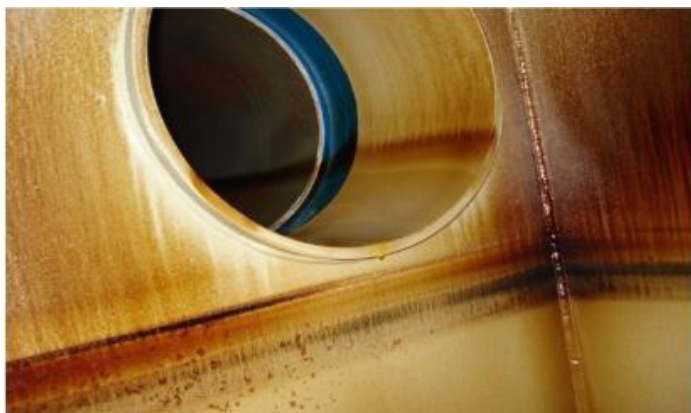
- Initiation (caused by heat and natural degradation of the hydrocarbon)
 - $RH \rightarrow R\cdot$
- Propagation
 - $R\cdot + O_2 \rightarrow RO_2\cdot$
 - $RO_2\cdot + RH \rightarrow RO_2H + R\cdot$
- Decomposition
 - $RO_2H \rightarrow RO\cdot + \cdot OH$
- Termination
 - $R\cdot + R\cdot \rightarrow R-R$
 - $RO_2\cdot + R\cdot \rightarrow RO_2R$

"RH" represents a hydrocarbon molecule, such as oil. "R·" is a hydrocarbon free radical. "O₂" is oxygen. "RO₂·" is an alkylperoxy radical. "RO₂H" is a hydroperoxide (sometimes called a carboxylic acid). "RO·" is an alkoxy radical. "·OH" is a hydroxy radical. "RO₂R" represents nonradical products. Finally, the "R-R" represents polymerized hydrocarbons formed when two hydrocarbon free radicals react. The outcome reactions are the formation in the oil of oxygen-containing products such as acids, esters,

alcohols, ketones, polar compounds and polymeric materials. It has already been established that oxygen is polar, just like water is polar. Metal parts of a steam turbine are also polar. Polar compounds are attracted to one another; therefore, degraded lubricants can have a heightened affinity toward the metal turbine parts, where they will collect as a sticky plastic-like material called varnish, as shown in Figure 2.

Antioxidants function by reacting with lubricant degradation precursors during the propagation or decomposition stages, thereby slowing down the attack of the oil by oxygen. Sometimes, degraded antioxidant compounds (especially PANA – phenyl-alpha-naphthylamine – types) can also begin to accumulate into high molecular weight materials in the oil and deposit onto metal parts as varnish. When large quantities of varnish accumulate in the body of the oil, they begin to precipitate out of solution into a thick goeey layer called sludge, as illustrated in Figure 3.

Figure 2 – Varnish



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Figure 3 – Sludge



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Hydrolysis is another degradation mechanism by which varnish and sludge are formed within a turbine. It is a reaction of oxygenated esters and ketones (in used turbine oil) with a hydroxy group in water. (In a process called dissociation, water naturally breaks down into a weak acid and a hydroxy group.) Hydrolysis occurs as a reaction between the used turbine oil and the hydroxy group to make the lubricant have a stronger affinity to water and to metal turbine parts. This reaction step also increases the oil's tendency to emulsify with water, thereby increasing the rate of oil degradation and making water removal even more difficult.

The previous discussion may lead a steam turbine operator to ask, "I must run my turbine reliably. Given all of these issues with the turbine oil, how can I do this?" Fortunately, there are solutions.

Lubrication reliability program

A lubrication reliability program for steam turbines must include:

- High-performance lubricant
- Proper installation of new lubricant
- In-service activities
 - Purification (contamination control)
 - Condition monitoring

High-performance lubricant

Steam turbines are moneymakers for power plants, making them extremely critical pieces of machinery. It seems like common sense that any turbine operator would want to choose a high-performance lubricant. So, how does one determine the difference between turbine lubricants and the right one to use? The average consumer often shops for the lowest price, assuming that it is the best value. Low price does not necessarily represent the best value when shopping for steam turbine lubricants. In addition, it is a mistake to focus only on a single performance property when trying to choose the right high-performance turbine oil. Instead, look for a balanced mix of all properties to ensure best overall performance. Table 3 lists the desired properties that should be considered when evaluating steam turbine oils, as well as the benefits of each.

Table 3 – Lubricant Properties & Benefits

Properties	Benefit
Oxidation resistance	Reduces the formation of varnish, sludge, emulsion & entrained gas/foam
Corrosion prevention	Prevents rust, minimizes acid attack of copper alloy parts
Water separation	Makes water removal easier, reduces hydrolysis, increases oil life
Gas/foam release	Less oxidation, improves lubricity, no cavitation
Contaminant handling	Good oil degradation solubility, improves filtration/purification

Is it possible for steam turbine oil formulations to provide all of the benefits listed in Table 3? Yes, it is. Formulation scientists have numerous base fluids and additives available for their steam turbine oils. The proper components must be chosen, blended and tested to create a synergy between the base fluid and the additives. Recent research has shown that any or all of the features listed in Table 3 can be detrimentally affected if the wrong base oil or additives are chosen. For example, some of the performance issues mentioned previously have often been traced back to industry-wide changes in lubricant base fluid refining techniques and/or antioxidant selection.

While the lubricant is what will be installed into the steam turbine, it should only be considered part of product being selected. The product should also come with support services. A good lubricant supplier should be able to provide support services and knowledgeable field representation. A lubricant representative should be able to provide expert advice about turbine oil as well as lubrication reliability recommendations to protect the lubricant when it is in service. This person also should be readily available in times of need. Finally, the turbine operator should verify that the lubricant supplier is able to support the field representative, to answer questions the representative does not know, and to deliver the lubricants and services promised.

When courting potential steam turbine suppliers, it is important to ask a few questions, including:

- Does the oil meet OEM requirements?
- Does the supplier have a formal program for turbine oil delivery?
- How will the oil be delivered?
- What steps are taken to ensure that the oil is not contaminated during transport?
- What are delivery lead times?
- How does the supplier intend to support the product after installation?

After the OEM approvals have been verified and distribution information gathered from suppliers, the number of acceptable vendors should be dramatically reduced. The next step is to consider oil compatibility and oil vendor services offered to aid in an oil change or addition. Unless a power plant is being started up for the first time, there is probably oil already in service in the steam turbines. The best lubrication practice is to completely drain, clean and refill a steam turbine when changing oils. Unfortunately, this is often impossible due to production and scheduling limitations. In such cases, it is extremely important that the supplier be capable of providing compatibility testing. If the supplier is unable to provide this service, the power plant should employ a testing lab. If the new oil is found to be incompatible with the oil currently in service in the steam turbine, mixing the oils could lead to more problems than the operator had before the change.

Proper installation of new lubricant

After the oil has been chosen for a steam turbine oil conversion or oil sweetening, the real work starts. A good lubrication reliability program should include installation procedures. It was mentioned previously that many steam turbine operators have been experiencing challenges. If a changeover to new oil is not conducted properly, the conversion could provide no benefit, or sometimes make matters worse. The system must be properly drained and inspected. The steam turbine reservoir should be inspected for sludge and varnish. If sludge and varnish is observed in the reservoir, it is very likely that it is present in the pumps and piping within the turbines oil circulating system. The operator must clean the turbine or – if lacking the expertise – must hire a professional firm to do it. It is vital that the steam turbine is properly cleaned and flushed prior to addition of the new lubricant. When a new lubricant is dispensed into the system, it can churn up any varnish and sludge present in the system. In this case, worse oil performance can result.

In-service activities

An effective lubrication reliability program for steam turbines must include preventive maintenance activities, including purification and condition monitoring.

Oil purification (contamination control)

Removal

To obtain maximum performance from a steam turbine and the turbine oil contained within, it is important to remove any contamination that might be present or introduced into the oil. Contamination can be the catalyst to oil degradation, which results in reduced reliability of the turbine. Some turbine OEMs will supply purification systems with the turbine during the installation, but depending on the age of the turbine or the contaminant to be removed, it may not be best for the intended job. The term purification can be representative of various oil cleaning techniques, depending on the contaminant to be removed. The most common purification technique for removal of solid contamination is filtration. If the contaminant to be removed is water, the most common purification devices are called separators.

Separators for removal of water from steam turbine systems include these various types:

- Gravity
- Centrifugal
- Coalescing
- Absorbent polymer
- Vacuum distillation

To remove other contaminants, such as solid and soft contaminants, the main purification technique is filtration. The two main filtration types are primary and secondary. Primary filtration systems are often called inline filtration systems. Secondary filtration systems, frequently used in conjunction with primary systems, are often called kidney-loop filtration systems. Primary filtration requires high oil throughput, thus is not usually as effective as primary and secondary systems used together. Secondary systems are used to filter the oil separate of the bearings in the turbine. Primary and secondary filter systems use similar media.

Common filter media include:

- Cartridge-type containing paper, fiber glass or synthetic polymers
- Depth filtration using roll-type paper or particulate solids, such as clay
- Electrostatic
- Ion-exchange media

Prevention

Another popular way to control contamination is to prevent it from getting into the steam turbine from the start. Several techniques have been used to accomplish this. One common technique is air filtration; another is controlled air addition to the system. A common air filtration device is the desiccant breather. Outside air is drawn through the desiccant breather on its way into the steam turbine oil system. The breather removes both water vapor and dirt from the air so that these contaminants do not infiltrate the oil. With controlled air addition, the technique is to push a positive pressure of either dry air or an inert gas, such as nitrogen, into the steam turbine oil system. In this case, the positive pressure on the system keeps contaminated air from entering the turbine's oil system.

Oil condition monitoring

After high-quality oil is installed into a steam turbine and high-performance purification equipment is employed, a monitoring program must be implemented to evaluate the condition of the oil. Whole papers have been written on the subject of oil analysis, but – as a brief overview – an effective oil analysis program should include four main activities:

- Test selection
- Lab selection
- Establishment of action limits
- Use of the report

The main question for the turbine operator trying to establish an oil analysis program is what tests should be run? Unfortunately, many commercial laboratories have simplified their programs to provide test packages based upon very broad categories, such as industrial oil analysis or engine oil analysis. The trouble with these test programs is that they can often include tests that are unnecessary or miss tests that may be critical to the specific application of interest. In this case, there are specific tests that should be considered for proper evaluation of steam turbine oil. Table 4 provides a list of traditional tests routinely employed for industrial oils at commercial labs vs. a list of tests that should be considered, with specific choices dependent upon the current operation of the turbine.

Table 4 – Turbine Oil Testing

Traditional Turbine Oil Tests	New Turbine Oil Tests for Consideration
Viscosity @ 40°C	Viscosity @ 100°C and 40°C + VI (ASTM D445 & D2270)
Water by Crackle	Water by Karl Fischer (ASTM D6304)
Oxidation by FTIR	Oxidation by FTIR
Acid Number	Acid Number (ASTM D664)
	RULER – Remaining Useful Life (ASTM D6971)
	Membrane Patch Colorimetry (MPC) – Varnish Potential
	Foam (ASTM D892)
	Air Release (ASTM D3427)
	Water Separation (ASTM D1401)
	Rust Test (ASTM D665A=DI Water / ASTM D665B=Sea Water)
	RPVOT – Rotating Pressure Vessel Oxidation Test (ASTM D2272)
	Particle Count (ISO 4406-1999)

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