# "Steam Turbine Oil Conditioning and Operational / Environmental Impact"

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**STEAM TURBINE AND GENERATOR EFFICIENCY, AVAILABILITY AND RELIABILITY IMPROVEMENTS**

**Argument**

Assuming factual the statement that steam turbine efficiency is more complex than simple, we might start with simply breaking down what it means pragmatically to talk about efficiency. In terms of both operational and environmental concerns, as the title to this paper brings to bear, efficiency might be most simply seen as the relation between the energy put out by a system to the energy put into the system. For example, with a coal-fired steam turbine, this efficiency would be the inverse of the ratio of the BTU energy value of the coal used to produce the steam to drive the turbine to the energy output from the turbine's generator, translated to its BTU value.[1] Due to heat loss and friction, energy input is lost at each sub-system of the steam turbine, in addition to the high and low pressure turbines: coal pulverizers, boilers, hydraulic control systems, moisture separators, generators, even the oil lubrication system, etc. Each might be analyzed separately in a study of efficiency to determine where the major losses occur, as each system has or is characterized by different efficiencies. Fully understanding steam turbine efficiency lies in the complex interrelatedness of each of these subsystems. For turbine and component manufacturers, the goal is to produce and sell the most efficient system; for the plants that operate them, the goal is to maintain the peak operational efficiency capable within each independent system.

To this last point we will focus the discussion here – maximizing operational efficiency at the plant level and thereby producing both the greatest return on investment for the cost of the steam turbine system and associated maintenance costs, but also resulting in the least impact to the environment. It will be easier to suggest an argument in favor of lessening the overall environmental impact of power plants particularly, when efficient and cost-effective operational

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[1] Even this does not account for the already generated electrical energy to each sub-system that would be separate from the energy value of the coal being consumed.

practices are easily the best practices for the environment, as perhaps they are in the case of maintaining lubricating oils. To our stated purpose, we will make the argument for the best possible conditioning of the turbine oil lubricating system, and look theoretically at how the connection between efficiency within the steam turbine system impacted by lubrication quality could suggest reduced emissions to the environment. This environmental benefit further supports the argument for the case of optimum oil conditioning in maintenance practice. But first, how might we define "optimum oil conditioning," and what are the operational benefits of this practice?

**Operational Benefits**

In order to define, we must first understand that optimum oil conditioning cannot be separated from the operational benefits it is intended to deliver. For a power plant, the primary goal is the generation of electricity to meet the market demand at any time. To accomplish this, the condition of the equipment must be maintained in as nearly new condition, meaning peak efficiency, as possible. Hence, from a lubrication standpoint, all metal components must be adequately lubricated to protect from wear. The condition of the oil should at a minimum meet the equipment manufacturer's recommendation, but exceeding these recommendations is perhaps better/best practice. To the specific case of the series of steam turbines (both high pressure and low pressure) that make up a single system, and the critical interface between the bearings and the turbine shafts within that system, typical turbine oil recommendations call for a minimum maintained oil cleanliness of $5\mu$ for particulate and 150 ppm for total water. These specifications accomplish two things: keeping particulate of $5\mu$ micron and larger out of the lubrication system to a certain efficiency (Beta 1000, for example) minimizes to nearly negligible the abrasion that might occur at today's designed clearances between the journal and the bearing; adequate "dryness" of the oil, at the 150 ppm specification or even lower, maintains the lubricity of the oil and thereby the proper film thickness between the journal and the bearing, preventing the negative effect of "wiping" of both the journal and the bearing from metal to metal contact. In each instance, particle or water damage of the metal components in the system leads to lost efficiency, but also potentially costly repairs to the turbines' shaft and multiple bearings. Thus, we cannot separate optimum oil conditioning from the operational benefits: that is, maintaining optimum oil condition, that which meets or exceeds what turbine manufacturer's specify, produces the lowest cost to operate by creating the longest bearing life or L10 life, the longest oil life, and the least potential downtime due to forced outages, perhaps the greatest threat to the primary goal of the power plant as stated above.[2] (We will come back to the dollar value of these costs a little later.)

The question now is how we maintain the oil in its optimum condition to assure both peak efficiency and continuous power generation as needed. It is perhaps too simple and obvious to say that "to maintain oil in its optimum condition we must first know that we are," but this is the point that must be accepted without question. A proper oil analysis program, whereby we know the condition of the oil within the system at any given time and how it is affected by various events, including the changing of the seasons, can assure us that no damage is occurring to those critical components within the system. An oil analysis program should be implemented upon installation of the turbine system: this is perhaps nowhere more critical than with steam turbines, where there is greater potential for water ingression, not just from humidity in the

[2] As is commonly defined, the L10 life is the time it takes on average before 90% of a group of bearings subjected to the same loads will begin to show fatigue. The goal for properly maintaining the lubrication to the bearing and the journal in the case of steam turbines is to meet and possible extend this time before any repair has to be made to the bearing.

environment and the resulting condensation but from a potentially disastrous seal leak.[3] General recommendation within the industry is for a minimum of every three months, but performing analyses on every separate main lubrication reservoir dedicated to each steam turbine system on the order of every month would be better to establish trending of how the oil condition might change, even slightly, over the course of the year due to environmental conditions but also varying demands on the system at peak and off-peak times.[4] Plus, greater awareness at a greater frequency may allow actions to be taken that could save hundreds of thousands of dollars. The longer a system operates when the oil condition is less than optimal, the greater the potential damage.

Monitoring oil condition as above recommended will suggest that the oil conditioning system, whatever type it may be, is operating effectively, removing damaging particulate and water contamination and protecting the journal and bearings and other critical wear components. But, the protection suggested and provided is time-dependent to the given point in time of the oil sample. Keeping particulate to acceptable levels and maintaining those levels prevents the abrasive damage that may occur, and particulate filtration provided by pleated, micro-glass cartridges is broadly, if not exclusively, accepted as the best method. But water, which may be the more damaging contaminant as it effects viscosity, lubricity and thereby film thickness, deserves special consideration. Just because the total water meets or falls below the recommended specification of 150 ppm does not mean that the turbine system is adequately

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[3] "The shaft seal on a turbine rotor . . . presents a long, tortuous path for any steam leaking through the seal. The seal therefore does not prevent the steam from leaking. The leaking steam is collected and returned to a low-pressure part of the steam circuit." (http://www.energy.qld.gov.au/electricity/infosite/index.htm). In many cases, the leaking steam will carry over into the lubrication system.

[4] The Electric Power Research Institute (EPRI) recommends certain minimum tests be conducted every three months, including particulate, water, viscosity, and lubricity, but for the purposes of argument here, we will emphasize that particulate counts to ISO 4406:1999 and total water by Karl Fischer should be done every month, as these two tests will inform if there is a change in the oil condition that alone can damage metal components such as increased particulates, or what might lead to the long term degradation of viscosity, oil lubricity, and the resulting loss of film thickness with increased total water counts.

protected. Here we will speak specifically of the steam turbine system and what is required for its adequate protection; for there is always the case of the "what if."[5] Water removal technology protects against this "what if." If a seal leak occurs and allows a sudden water ingression into the turbine oil reservoir, then the oil conditioning system is no longer there to maintain the condition of the oil, but rather it is there for preventing the system to be overrun and for protection of metal components in such an event. It is there to take the water out and keep the oil as dry as possible until what time a repair to the seal can be made. To this end, the best protection is provided by the technology that can remove water the quickest, remove the most damaging water (whether free, emulsified, or dissolved), and is the most reliable when needed and the most cost-effective to operate long term; meaning you can run the system the full time that the steam turbine system is operating with the least cost to operate and the greatest probability of working in such an emergency event.

In evaluating water removal technology, we do so then on these four criteria:

- Process Rate or (Water Removal Rate)
- Ability to Remove the Most Damaging Water or (Total Water Removal)
- Reliability
- Cost-Effectiveness to Operate and Maintain

First, not every power plant accepts the policy, or can appropriate the necessary capital toward that policy, that the best protection (and oil conditioning) for a steam turbine system is a dedicated turbine oil conditioning system, having both particulate and water removal capability. Too often remediation companies are used to "purify" the turbine oil reservoir once or twice a year during scheduled downtime. Or worse, they are called in when there is an emergency, when

[5] This is why we might see in the case of combined cycle operations that a manufacturer such as GE will specify particulate removal systems on both the gas and steam turbines, but will only specify water removal technology on the steam turbine. The water removal technology is there for the "what if": what if there is significant ingression of water into the lubrication system as would result from a seal leak. In each case, the technology for both is sold on the reservoir with the system, specified by GE. Not every manufacturer follows this model, but leaves it to the project management for installation to specify.

sampling reveals that the oil condition is beyond desired specifications. Another practice is to have a flushing system available internally for the regular purification of the oil reservoir or for emergency water situations; facilities will many times use centrifugation technology for this system because of its high water removal rate. But if it meets the first criteria above, why not dedicate the centrifuge to the reservoir full-time? This may be for different reasons, but primary is the reliability coupled with the operating costs for the centrifuge: the centrifuge with its myriad of moving parts itself requires regular scheduled maintenance, as much as every three months, and then an involved overhaul once a year.[6] As many power plant maintenance engineers suggest, the centrifuge's maintenance requirements make it unreliable to crisis situations. Plus, there is the additional issue of whether a centrifuge can effectively break an emulsion and thus remove all the free water in the turbine oil – free water being arguably the most damaging water to the bearings and journals, and leading to wiping.

In many cases, power plants have allocated resources and do have dedicated equipment for each reservoir. This may be of four basic types: the centrifuge, as already discussed, the gravity separation system, a coalescing/separating system, or one form of vacuum technology (distillation or dehydration). The centrifuge and the gravity separation system make use of the same force, except that the centrifuge mechanically increases gravity by as much as 2200 times. The gravity separation system is very common to older power plants and many still swear by it, but like the centrifuge it has its weaknesses based on the criteria above.[7] In the case of gravity separation, it would seem that no criterion is met, but it can and does keep the oil in optimal

[6] This comment is based on multiple conversations with power plants still using centrifuge due to lack of capital or other extenuating circumstances.

[7] Systems such as the Bowser 832-P are still in operation throughout the world, from the US to China, no matter which direction you travel. It is common that you will here the Reliability Engineer or Lubrication Specialist of the power plant swear by these systems: "I have been using it four 50 years and have never had a water problem." But this statement begs the question that we are attempting to answer here: that if you had a sudden water ingression, would the technology in the system be capable to the task?

condition if there is no sudden water ingression. As a system that relies primarily on gravity and passing the oil over a series of hydrophobic screens, it has one of the lowest water removal rates, will not effectively break an emulsion, and because of the low water removal rate is not reliable in the event of a leaking seal. It is, however, relatively simple and inexpensive to maintain. This brings us to a comparison between the two other technologies (coalescing/separating and vacuum) that are more commonly seen in newer steam turbine installations, at least those of the past 20 years, but also to many older steam turbines where power plants have upgraded to newer filtration technology because the threat of a seal leak may be even greater than in turbines with newer technologies and built to tighter tolerances. For a more detailed explanation of the differences between coalescing/separating and vacuum technologies, please see the cover article, "Oil and Water Shouldn't Mix," *Power Engineering*, April 2006. We will state simply that today's advanced coalescing/separating technology is currently the best at meeting the criteria established and thereby providing the best and most reliable dedicated turbine oil conditioning solution for main turbine reservoirs in power plants, even better than those hybrid coalescing/vacuum systems available on the market today.[8] Coalescing technology provides the best total water removal rate for the total operating costs in the event of an emergency seal leak.

Now to return to those potential costs associated with inadequate turbine oil conditioning. The purpose of dedicated filtration is to accomplish just one thing that goes to the bottom line for the power plants; as stated earlier, that is "the generation of electricity to meet the market demand at any time." It is the "any time" where dedicated filtration is absolutely critical. It accomplishes this by continually cleaning the oil to maintain ideal lubricity, thus reducing to negligible the coefficient of friction between the journal and the bearing and minimizing wear as

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[8] For a mathematical comparison of coalescing to combined coalescing/vacuum technologies, based on published water removal rates, please contact the author. A similar model was used to compare vacuum distillation to coalescing in the above referenced *Power Engineering* article.

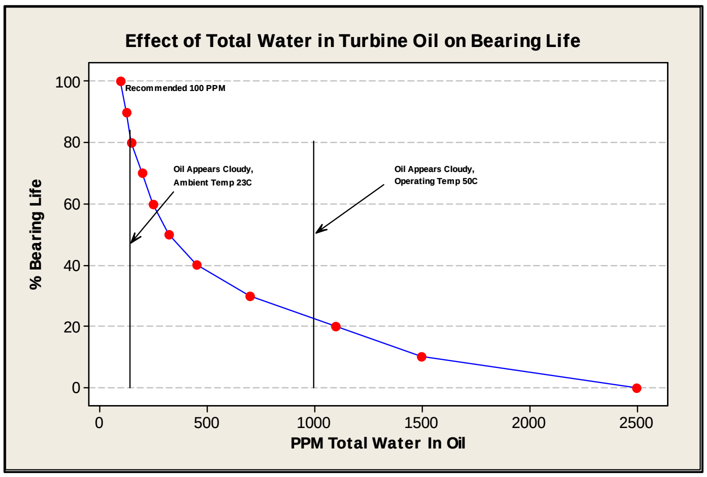
little as possible. To these effects – clean oil, negligible friction, and minimized wear – we can associate certain costs to be avoided, a return on the investment in the dedicated oil conditioning system. The savings result primarily from (1) fewer scheduled maintenances, (2) longer oil life, (3) maximum bearing life (the L10 life), and (4) greater energy efficiency (perhaps the most difficult to measure but what will be addressed later).

First, scheduled maintenance at most facilities is kept to twice a year during fall and spring outages, when demand for power is not at a peak. During this time, which can span 2-3 weeks per turbine or longer if the number of turbines per facility is less, multiple procedures may be performed: an oil flush (usually if dedicated filtration is not the norm), the addition of make-up oil if required, more detailed oil analysis than might be done during normal sampling, reservoir inspection, seal repair if required, and other inspections to determine if additional maintenance to sub-systems is necessary: pumps, motors, fans, gearboxes, coal pulverizers, boilers, generators, etc. As perhaps will be evident below, with proper oil conditioning and a comprehensive sampling program to establish a detailed trend line, maintenance might be scheduled only once yearly for many current twice-yearly practices. The only thing that might need the twice-yearly maintenance is the dedicated oil conditioning system.[9]

As to the more time-consuming and costly repairs such as replacing bearings or re-babbitting, these can be extended to longer intervals on average with adequate and dedicated oil conditioning. This goes to insuring the maximum potential of the bearing life, known as the L10 life – extending as long as possible the time to when first wear signs are indicated. Avoiding these more costly repairs is the goal; having to pull bearings for replacement or repair can cost more than $100,000 per bearing from the combined repair and the maintenance hours required

[9] Maintenance could consist then of a half-day to drain the oil from the system to a low-enough level to replace critical particulate and water removal elements and replace seals; keeping the system at optimal performing conditions until the next scheduled maintenance.

for the breakdown and reinstall.[10] The benefit of continually conditioning the oil while in use, keeping it to even below the turbine manufacturer's specifications will typically result in the potential for maximum bearing life. The emphasis is again on water being the most critical contaminant to control and keep to a minimum within the lubrication system. The graph below shows a theoretical comparison between total water content and bearing life.[11]




This indicates that dryness in the 100-150 ppm range will stand the best chance of realizing the longest life for the bearing. Typical questioning of reliability engineers and lubrication specialists at many facilities shows that total water in the 200-250 ppm is often an acceptable level; in the minds of many people, this does not constitute a "water problem." It is perhaps the filtration expert that is amazed at this level being acceptable at all or under any circumstances.

Both bearing life and fewer scheduled maintenances are the product of longer oil life: this is a logical given if the oil is conditioned properly while in use, especially with respect to keeping the oil as dry as possible. It is typical where dedicated filtration is the norm, that

[10] And with the greater desire to extend bearing life and equipment reliability, turbine manufacturers look to ever more-advanced and thereby expensive alloys for the babbitting of bearings and the coatings of turbine blades and other metal wear items. Repair and replacement costs can only go higher as a result, more than a simple adjustment due to inflation.

[11] Graph has been extrapolated from arguments that point to the detrimental impact of even small amounts of water to bearing life. See for example, Chris Rehmann, "Improvements in Bearing Life Using New Sealing Technology," Proceedings of the Twenty-Second International Pump Users Symposium, 2005.

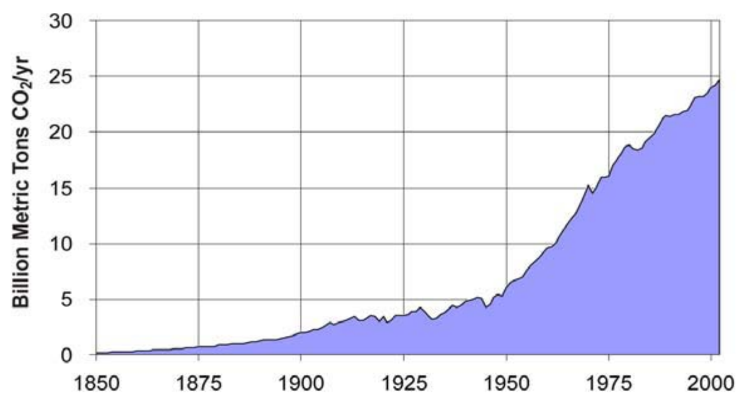
flushing (a flush here will be defined as a one-time purification of an oil reservoir to return the oil to as near a new state as possible) as a yearly or twice-yearly practice can be avoided; this results in an estimated $25,000 savings per flush for a 10,000-gallon reservoir. And, as we may commonly see where dedicated filtration is the policy, oil life may be extended to 25 years or longer. But without adequate filtration, we could see oil replacement on the order of every 5 years; in a recent conversation with a Chevron Corporate Account Manager from Malaysia, it was indicated that replacing turbine oil every 5 years is the norm throughout much of Asia, Indonesia, and Malaysia. The difference between a 5-year replacement and a 25-year replacement, at today's turbine oil prices (on a 10,000-gallon reservoir) would result in a $600,000 greater cost if replacing every 5 years.[12] It should be easy to see the simple justification needed for an oil conditioning system for a 10,000-gallon reservoir that might cost only $100,000 USD. Add to the replacement costs the potential disposal costs that could be as much as $5 per gallon and it is hard to fathom why changing out the oil every 5 years would be an acceptable practice.

**Environmental Impact**

This brings us to the more complex measurement of energy efficiency for the steam turbine system as it might result from optimum oil conditioning. It is here that we can posit theoretically the environmental benefit that oil conditioning can impact, simply in the matter of reducing oil waste and more complexly in reducing the amount of energy consumption (energy input) of the steam turbine system. For the environment, this is particularly critical in the case of coal, as already suggested, and as certainly is the focus of most environmental concerns resulting in regulation, but also in improved technologies to make more environmentally friendly what is

[12] Estimate is based on conservative price of 15 USD per gallon of typical ISO 32 turbine oil.

still the most abundant and practical resource for power generation. In addition to new alloy materials for surfacing both journals and bearings to improve efficiencies, recent efforts to lessen the environmental impact of fossil fuel burning include $CO_2$ Capture and Sequestration, represented in fuel decarbonization efforts, oxy-fuel firing, and post-combustion capture which is common through several means.[13] Other efforts look to the more complex but still more promising coal gasification technology with expected increases in power plant efficiencies from 33% to 60%, with reduced $CO_2$ emissions of as much as 50%.[14] The below chart indicates the historical increase in $CO_2$ emissions toward the total greenhouse gas effect.[15]

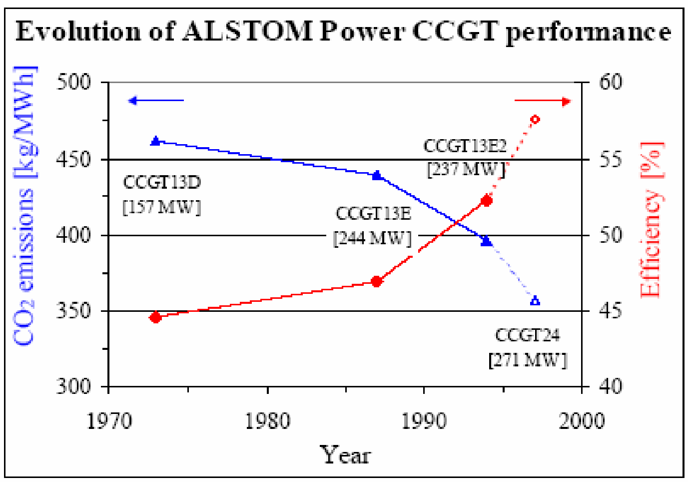



Data Sources: Energy Information Administration, International Energy Outlook, Carbon Dioxide Information and Analysis Center (CDIAC)

(While $CO_2$ is increasing, $SO_2$ and NO are decreasing, making $CO_2$ emissions of the greater concern.) While each of the aforementioned ideas for reducing $CO_2$ emissions has their benefit, they can affect negatively the overall efficiency of the power generation process due to their significant energy and in some cases infrastructure requirements. This becomes the tradeoff, indicating more analysis be done for the best overall plan to lessen environmental impact.

[13] For a more-detailed explanation of these processes and the attraction or detraction to each as a viable means for lessening the environmental impact, see "Controlling Power Plant $CO_2$ Emissions: A Long Range View," Marion, J., Nsakala, N., Griffin, T., and Bill, A.; www.netl.doe.gov/publications/proceedings/01/carbon_seq/1b2.pdf.
[14] Cited in "High-Efficiency Coal/Solid Feedstock: Advanced Gasification System," *US Climate Change Technology Program: Technology Options for the Near and Long Term*, November 2003, Page 63.
[15] Excerpted from, "Carbon Sequestration Technology and Roadmap Plan 2006," National Energy Technology Laboratory, June 2006.

If we can assume the connection between efficiency and reduced emissions, then a program directed toward improving efficiency as it results from standard best operational practice, as with the case of oil conditioning, might be viewed as a no-brainer. Considering the financial numbers above, the justification and ROI apparent should make this a simple conclusion to draw, but where facilities around the world are still replacing oil every 5 years, something is amiss. In the next chart, we see the evident correlation between efficiency and lessening of the environmental impact:[16]




While the chart focuses on the primary correlation to emissions and efficiency for combined-cycle gas turbines of ALSTOM Power design and installation, the information is relevant to show that emissions might be drastically reduced by as much as 22% with just a 12-15% increase in efficiency of the total turbine system. These figures are in keeping with the projection above of a 50% reduction in $CO_2$ emissions for a 27% increase in efficiency. Thus, we might expect a reduction in emission of 1.4-1.8% for each 1.0 percent efficiency improvement; we will use the median of 1.6% for any future calculations, financial or otherwise.

[16] See note 12 for source information on chart.

We return again with where this diversion began: the impact of optimum turbine oil conditioning to turbine efficiency and the resulting environmental impact, now independent of the transparent cost savings which would justify the use of dedicated oil conditioning equipment separate from environmental concern and for any regulatory compliance, and even separate from energy input savings. To continue, the connection must be made theoretically, but logically, as no comprehensive study of ideal oil lubricity between metal components in steam turbines has been done; at least not discovered by this author at the time this was written. We come back to the correlation that ideal lubricity leads to reduced and minimum coefficient of friction which in turn leads to greater efficiency:

Ideal Lubricity ≈ Minimum Coefficient of Friction ≈ Greater Efficiency

Historically, it has been too commonly the industry argument that minimal increases in friction are more easily compensated by increased energy into the system to overcome the friction: "While the increased drive torque required to overcome the increased frictional resistance is of very little concern, the side effects of increased bearing temperature and wear of the bearing and/or journal are of major concern."[17] The goal has not been in lessening environmental impact, thought to be insignificant, but rather as stated, preventing the more "costly" bearing and journal wear. Such mindset reflects perhaps a historical circumstance of low fuel prices that would make negligible the additional BTU value required to increase the drive torque.

We have continually made the argument that water is potentially the more damaging contaminant within the turbine lubrication system; because water has the greatest negative impact to the film thickness between the journal and the bearing. Viscosity breakdown, oxidation, and lost lubricity in the oil minimize film thickness – what results from the

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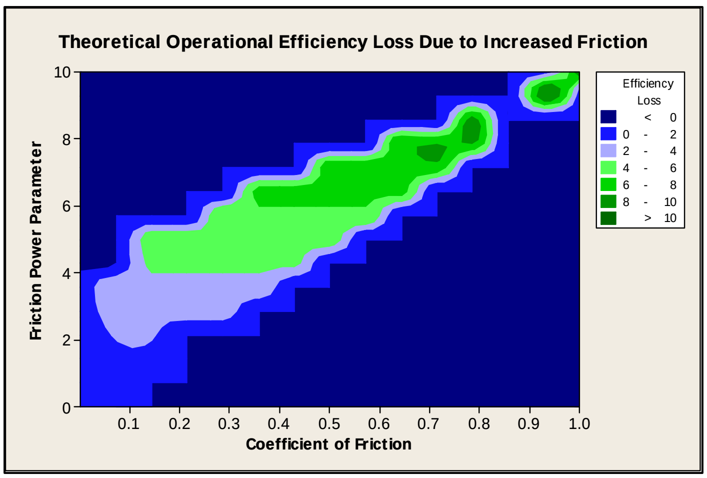
[17] Electric Power Research Institute, *Guidelines for Maintaining Steam Turbine Lubrication Systems*, "Bearing Lubrication Principles," 1986, 6-3.

detrimental effect of total water greater than the saturation point of the turbine oil. This "loss" increases the load on the shaft and the bearing, leading to wiping, and the potential decrease in the realized life of the bearing. At a minimum, it contributes to a greater potential for premature failure resulting in costly forced outages. The increased coefficient of friction and the corresponding energy input into the system to overcome this friction is what drives the loss of system efficiency. We might represent this theoretically in the following graph:




The full impact to the coefficient of friction can vary; depending on the negative impact that water may have on all bearings and shafts that make up today's modern main steam turbine system (comprised usually of one high-pressure turbine and three low-pressure turbines). Primary variables include load, speed, and resulting oil viscosity; secondary variables include clearance, oil flow, and surface roughness as a result possibly of abrasion. We can only speculate, without further study, that the loss in efficiency might be in the range of less than 1% to more than 10%. Coming back to consider what might be a negligible to "minor" energy input to overcome the increased friction, the resulting emissions increase could be in the order of 1-16% – certainly not negligible in today's climate.

## Conclusions

If we take the average steam turbine size to be about 350MW and we lose over the 10-12 years of the L10 bearing life a total of (conservatively) 3% efficiency capability of the system, this can translate to a loss of 10.5MW generating loss at any given time or 10.5% greater energy input to overcome. Looking at it from the market side, there is an easier value to associate with this 10.5MW-equivalent loss (at a typical $25 EBIT per MW/Hour): at 300 generating days on average per turbine system, at 24 hours for those 300 days, and 10.5MW loss per hour, at a market value of $25 EBIT, the loss could conservatively be in the $1.9M USD range. We can see how this translates into the greater energy input required to maintain system efficiency under these circumstances; costing potentially 20-25% this figure, again justifying financially a dedicated oil conditioning system to prevent the potential loss. The impact to the environment is seen in the increased $CO_2$ emissions as well as $SO_2$ emissions and other harmful emissions of coal-fired power plants. If coal is to remain the most dominant fuel source to drive power generation (at approx. 40% world-wide), then it makes common sense to optimize operational efficiencies that impact positively on reducing current estimated global emissions:[18]

- 7.7 Million Metric Tons of $SO_2$
- 3.1 Million Metric Tons of Nitrogen Oxide
- 5.9 Billion Metric Tons of $CO_2$

If dedicated turbine oil conditioning easily justifies "across the board," then why would we not escape the culture and policies of the past when fuel and energy were cheap? Again, common sense should apply. The need to lessen the environmental impact should be a motivator, if not over the operational benefit, then as a significant addition to it.

[18] Energy Information Administration, Report #: DOE/EIA-0383(2006).