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Improved Plant Performance and Reduced CO_2 Emission Through State-of-the-Art Condenser Cleaning And Air In-leakage Detection

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ABSTRACT

Efficient condenser operation is critical to minimizing the operating costs and improving the performance of a turbogenerator unit or power plant. Efficient condenser performance is recognized by an improvement in heat rate and generation capacity, less fuel is consumed and a significant reduction in CO_2 emissions can be achieved. Condenser tube fouling, fouled external surfaces of Air-Cooled Condensers (ACC) and condenser air-inleakage have been found to have a significant impact on condenser performance and subsequently plant performance. *State-of-the-Art* technologies have been developed to effectively remove fouling and deposits from condenser tubes, finned external surfaces of ACC's and to identify the location of air and water in-leakage into the condenser, providing a longer useful life cycle. In addition, application of these technologies results in improved condenser backpressure, a decrease in plant heat rate and a decrease in yearly fuel consumption. Overall, plant performance is improved and CO_2 emissions are reduced. Technology and cases are presented.

KEYWORDS: Condensers, Performance Improvement, CO_2 Emission Reduction, Cleaning, Air In-leakage Detection, Air-Cooled Condensers

CONDENSER PERFORMANCE

Condenser performance can have a significant impact on plant performance. Condenser design specifications define a maximum effective rate of removal of the latent heat in the exhaust vapor entering the condenser, as well as its transfer into the circulating water, given the condenser backpressure, cooling water flow rate and inlet temperature. Variations in the parameters will change the backpressure and also affect the heat rate for a given load. In addition, variations in fouling conditions and air in-leakage can negatively affect backpressure and heat rate. To avoid the negative affect maintenance personnel will routinely perform condenser cleaning and repair leaks within the vacuum boundary. However, the condenser cleaning must be effective to achieve improvements in performance and the sources of air in-leakage must be detected before they can be repaired. The result of cleaning will be improved heat transfer efficiency and improved condenser performance. Reductions of air in-leakage will also result in improved condenser performance. In this way, steam will be cooled efficiently, turbine capacity will not be restricted and less fuel will be consumed by the boiler.

Unfortunately, condensers seldom operate under clean conditions for very long periods of time and the ills to which they are prone during normal service fall into these major categories:

- Fouling of the tube surfaces
- Tube or Tubesheet Fouling due to shell fish or debris
- Reduced or restricted cooling water flow rate
- External surface fouling (of air-cooled Condensers)
- Circulating water in-leakage
- Excess ambient air in-leakage

The first four categories are related to fouling and tend to be cyclical in nature. The actual fouling impact will vary from plant to plant and even between units in the same plant. Fouling may also be impacted by cooling water flow rate. The last two categories are concerning water or air in-leakage. Either kind of leak is almost certain to develop at some point in the future, and a correction strategy can be prepared.

Fouling Of The Tube Surfaces

Almost every condenser experiences some kind of tube or tubesheet fouling, Most condenser circulating water sources contain dissolved solids that can precipitate and become deposited on the inner surfaces of the tubes, so adversely affecting the unit heat rate and/or limiting generation capacity. With exception given to titanium and superferritic stainless steel tubing, these deposits can also contribute to various types of corrosion and, if not removed periodically, the corrosion may eventually penetrate the tube wall, allowing circulating water to leak into and contaminate the condensate.

Fouling can affect not only unit heat rate but also the ability of the turbine to generate its design load capacity. In fossil-fired plants, an increase in heat rate is reflected in higher fuel costs for a given load and increases of 2% are not uncommon. Increased fuel consumption results in greater CO_2 emissions. In both fossil and nuclear plants, if the fouling becomes severe, it will cause the backpressure to rise to its upper limit, forcing a reduction in generated power. There are reports of up to 20 Mw having been recovered and tons of CO_2 emission reductions achieved by the removal of severe accumulations of deposits.

With nuclear plants, there is less flexibility and it is considered good practice to clean condensers at every refueling outage. Even where a nuclear unit is equipped with an on-line cleaning system, an annual or biannual off-line mechanical cleaning assures that condenser effectiveness will be maintained. And, in the absence of corrosion resistant tube materials, effective cleaning reduces the risk of pitting from the stagnant water in those tubes which may become blocked by stuck sponge balls. Further, effective cleaning ensures that every tube is cleared and cleaned at least once or twice a year.

Tube Or Tubesheet Fouling Due To Shell Fish Or Debris

When this occurs, the circulating water flow becomes restricted and the thermal conductivity of the tube side water film is reduced, again affecting heat rate and/or generation capacity. Putman and Hornick(1) found that a useful estimate of the circulating water flow rate could be obtained by interpreting condenser operating data in terms of turbine heat balance and low pressure expansion line relationships. Their reference plant was located on the Gulf of Mexico, where shellfish attached themselves to both the tubes and tubesheets, causing condenser performance to decrease fairly rapidly. ASME type single-tube heat transfer calculations were used to estimate fouling resistance, based on the observed variation in water flow rate. Plots showed a close and cyclical (saw-toothed) relationship between flow rate, fouling resistance and backpressure, a study of which allowed intervals between tubesheet cleanings to be extended, rather than conducted at fixed intervals.

External Surface Fouling (of air-cooled condensers)

From Putman and Jaresch(2), we know the external surfaces of the finned tubes on air-cooled condensers are very prone to fouling from pollen, dust, insects, leaves, plastic bags, bird carcasses, etc. Not only is the air flow affected but also the heat transfer coefficient, the deterioration in performance increasing unit operating costs. In severe cases, fouling can also limit the power generation capacity of the turbogenerator.

Further, under high ambient air temperatures, operators will sometimes spray water on the heat exchanger to reduce surface temperature. Unfortunately, depending on the quality of water used, this sometimes leads to a new scale formation on the tube fins. Note that air-cooled condensers operated in this way are not to be confused with Wet Surface Air Cooled Condensers.

Circulating Water In-leakage

Circulating water in-leakage can result from penetrations through the tube walls, from joints between the tubes and tubesheet that have developed leaks, or from other penetrations between the water box and condenser shell that have lost their integrity. The contaminants in the circulating water change condensate chemistry and/or pH, tending to increase boiler or steam generator corrosion; or result in an increased consumption of water treatment chemicals in the attempt to compensate for the change in water chemistry. Poor water chemistry can also cause stress corrosion cracking of steam turbine components.

Even a small circulating water in-leakage into the condensate can be damaging to the unit as a whole and is often the cause of an unscheduled outage. The length of that outage will depend on the means adopted to locate the source of the leak quickly, the on-line and off-line use of tracer gas (SF_6) being the preferred method.

The EPRI Condenser In-Leakage Guideline(3) explores these problems in detail and shows how the use of the tracer gas referred to above can be used to rapidly locate the source of either water or air in-leakage, allowing the problem to be corrected quickly.

Excess Ambient Air In-leakage

The design of condensers routinely allows for a normally acceptable level of air in-leakage, often considered to be 1 scfm (2.13 kg/h) per 100 MW, although a new ASME Standard(4) shows the limit to vary with the number of condenser compartments and exhaust flow rate. The sources of such leaks can be labyrinth glands on steam turbine shafts, as well as packings and seals that are less than leak-tight. As with fouling, air in-leakage rates above the acceptable values can detrimentally affect heat rate as well as limit generation capacity. Excessive air in-leakage also affects the concentration of dissolved oxygen in the hotwell, which can cause corrosion damage to other parts of the unit. Of course, high dissolved oxygen levels can also be caused by a change in the performance of the air removal equipment and this should be checked before undertaking the search for leaks. In many cases, the increased reliance on deaeration taking place within the condenser makes minimizing air in-leakage even more important.

CONDENSER CLEANING METHODS

Regardless of the tube material, the most effective way to ensure that tubes achieve their full life expectancy and heat transfer efficiency is to keep them clean. Each time the tube deposits, sedimentation, biofouling and obstructions are removed, the tube surfaces are returned almost to bare metal, providing the most effective heat transfer and the tube itself with a new life cycle, the protective oxide coatings quickly rebuilding themselves to re-passivate the cleaned tube.

Of the cleaning procedures performed *off-line*, mechanical cleaning is an economical and effective means to achieve good results.

Among other off-line methods is the use of very high-pressure water but, since the jet can only be moved along the tube slowly, the time taken to clean a condenser can become extended. Great care must be taken to avoid damaging any tubesheet or tube coatings which may be present; otherwise the successful removal of fouling deposits may become associated with new tube leaks or increased tube sheet corrosion, only observable after the unit has been brought back on-line.

Mechanical Cleaning of Condenser Tubes

Off-line mechanical cleaning is especially useful where fouling problems exist and are too severe to be handled by any of the other methods. Obviously, the tool selected has to be the most appropriate for removing a particular type of deposit. Molded plastic cleaners (pigs) are quite popular for some light silt applications. Brushes can also be used to remove these soft deposits as well as some microbiological deposits. Brushes are also useful for cleaning tubes with enhanced surfaces (e.g. spirally indented or finned); or those tubes with thin wall metal inserts or epoxy type coatings.

With harder types of deposit, metal cleaners of various designs have been developed, often with a particular deposit in mind. Figure 1.0, the Type C3S Tube Cleaner and Figure 2.0, the Type C4S Tube Cleaner show some of the current versions of mechanical cleaners with spring-loaded blades.

The blades are mounted on a spindle, a serrated plastic disk being placed at one end of the spindle to allow a jet of water to propel the cleaners through a tube with greater hydraulic efficiency. The water is directed to the tube being cleaned by a water gun, shown in Figure 3.0, Water Gun. The water is delivered by a pump operating at 300 psig (2.07 MPa). Since the pump is usually mounted on a wheeled base plate, the system can be conveniently moved from unit to unit within a plant or even moved to another plant. See Figure 4.0, Portable Booster Pump.

Another advantage of using water for tube cleaner propulsion is that the material removed can be collected in a plastic container for later drying, then weighing to establish the deposit density (g/m^2) and followed in many cases by X-ray fluorescent analysis of the deposit cake.

A water pressure of 300 psig (2.07 MPa) is very effective for propelling the cleaning tools through the tubes, while also preventing their exit velocity from rising above a safe level. Some other cleaning systems use air or a mixture of air and water to propel the cleaner, but air pressure is compressible and dangerous to use.

Most metal cleaners are designed to have a controlled spring-loaded cutting edge: but, if effective deposit removal is to be the result, the dimensions of the cutting surfaces have to be closely matched to the internal diameter of the tube being cleaned, not only to improve the peripheral surface contact but also to ensure that the appropriate spring tension will be applied as the cleaner is propelled through the tube. See Figure 5.0, C4S Tube Cleaner in Action. The effective life of cleaners designed in this way can be as high as 12 tube passes.

Tube cleaner innovations

As a result of an innovative research program organized to resolve problems encountered in the field and to develop new products where existing equipment was found to be inadequate, new tube cleaners were developed. For example, in order to provide the blades with more circumferential coverage of the tube surface, the cleaner shown in Figure 6.0, Hex Cleaner, was developed. The increased contact surface provided by the greater number of blades was found to be more efficient in removing tenacious deposits such as those consisting of various forms of manganese.

A later development involved a tool for removing hard calcite deposits, which were found to be difficult to remove even by acid cleaning. This tool, shown in Figure 7.0 and known as the Cal Buster, consists of a teflon body on which are mounted a number of rotary cutters. These are placed at different angles around the body, which is fitted with a plastic disk similar to those used to propel other cleaners through tubes. Used on condenser tubes that had accumulated a large quantity of very hard deposits, Stiesma et al(5) described how cleaners of this type removed 80 tons (72.48 tonnes) of calcite material from this condenser. It has now become a standard tool whenever hard and brittle deposits are encountered.

Additional developments for the removal of manganese dioxide, iron, and silica deposits, include the stainless steel brush (SSTB), it is made from stainless steel, with over 1,000 contact points per cleaner, Figure 8.0 shows the Stainless Steel Tube Cleaning Brush.

The experience gained from using these techniques has allowed the time to clean to be forecasted with confidence and cleaning to be performed to schedule. For instance, a normal crew can clean 5,000 tubes during a 12-hour shift. Clearly, this number can rise with an increase in crew size, limited only by there being adequate space in the waterbox(es) for the crew to work effectively

The concern is occasionally expressed that mechanical cleaners can possibly cause damage to tube surfaces. With cleaners that have been properly designed and carefully manufactured, such damage is extremely rare. Indeed, Hovland et al(6) conducted controlled tests by passing such cleaners repeatedly through 30 feet long, 90-10 CuNi tubes. It was found that, after 100 passes of these cleaners, the wall thickness became reduced by only between 0.0005 and 0.0009 inches (12.5 and 22.86μ). If a 50% reduction in wall thickness is the critical parameter, extrapolating this series of tests would be equivalent to 2,800 passes of a cleaner per tube, or 1,000 years of condenser cleaning!

Clearly, all off-line cleaning methods sometimes need assistance where the deposits have been allowed to build up and even become hard. In such cases, it may still be necessary to acid clean, followed by cleaning with mechanical cleaners or high-pressure water to remove any remaining debris.

Chemicals are also used for the off-line cleaning of condenser tubes: several mildly acidic products are available and will remove more deposit than most other methods; but it is expensive, takes longer for the operation to be completed, and the subsequent disposal of the chemicals, an environmental hazard, creates its own set of problems. It has also been found quite frequently that some residual material still needs to be removed by mechanical cleaning methods.

Very few on-line methods are available to clean condenser tubes but the best known is the system which uses recirculated sponge rubber balls as the cleaning vehicle. These systems often operate for only a part of each day and, rather than maintaining absolutely clean tube surfaces, tend to limit the degree of tube fouling. Unfortunately, although the tubes may become cleaner if abrasive balls are used, tube wear can now become a problem.

Mussalli et al(7) showed some uncertainty concerning sponge ball distribution and therefore, how many of the tubes actually become cleaned on line. It is also not uncommon to find that numerous sponge balls have become stuck in condenser tubes and these appear among the material removed during mechanical cleaning operations. For these reasons, the tubes of condensers equipped with these on-line systems still have to be cleaned periodically off-line, especially if loss of generation capacity is of serious concern.

Developing An Appropriate Cleaning Procedure

The selected cleaning procedure should remove the particular deposits that are present as completely as possible, while also causing the unit to be *out of service for the minimum amount of time*. Some other major considerations in the selection process are:

Removal of obstructions

Many tube-cleaning methods are ineffective when there are obstructions within tubes, or various forms of macrofouling are present and, clearly, those cleaning methods should be avoided. Attention has already been drawn to the shell-fish, which constitute macrofouling, including Asiatic clams and zebra mussels. The selected tube cleaner must have the body and strength to remove such obstructions. The cleaning method must also be able to remove the byssal material that shell-fish use to attach themselves to the tube walls.

There are certain types of other debris which can become obstructions, among them being cooling tower fill, waste construction material, sponge rubber balls, rocks, sticks, twigs, seaweed and fresh water pollutants, any or all of which can become lodged in the tubes and have to be removed. Meanwhile, experience has shown that, if appropriate procedures are followed, properly designed cleaners should not become stuck inside tubes, unless the tube has been deformed.

Removal of copper corrosion products

With condensers equipped with copper alloy tubing, copper deposits grow continuously and the thick oxide coating or corrosion product can grow to the point where it will seriously impede heat transfer. Not only will the performance of the condenser be degraded but such deposits will also increase the potential for tube failure. When a thick outer layer of porous copper oxide is allowed to develop, it disrupts the protective inner cuprous oxide film, exposing the base metal to attack and causing under-deposit pitting to develop. Such destructive copper oxide accumulations together with any other deposits must be removed regularly.

Surface roughness

Rough tube surfaces, as are created by the accumulation of fouling deposits, are associated with increased friction coefficients while the reduced cooling water flow rates allow deposits to accumulate faster. It has also been found that rough tube surfaces tend to pit more easily than smooth surfaces. Thus smooth tube surfaces, which result from cleaning, can improve condenser performance through:

- Improved heat transfer capacity and a lower water temperature rise across the condenser, reducing the heat lost to the environment
- Increase in both flow volume and water velocity, often resulting in reduced pumping power
- Increased time required between cleanings, by reducing rate of re-deposition of fouling material on the tube surfaces.
- Reduced pitting from turbulence and gas bubble implosion in copper alloy tubes.
- Longer tube life and condenser life

Plant performance will also be improved and CO_2 emissions reductions achieved.

Automated Cleaning Machine For Air Cooled Condensers

The automated cleaning machine, an example of which is shown in Figure 9.0, uses a significant volume of water; but at a pressure that, while allowing for effective surface cleaning, avoids damaging galvanized surfaces and fins. The main components of the system include a nozzle beam, a tracking system, and a control panel. The water contains no additives. The nozzle beam is optimally matched to the tube bundle geometry, with a constant jet angle. Optimizing the geometry of the nozzle beam involves determining the proper nozzle distance to the surface, the jet energy and the selection of the appropriate nozzle design. The constant jet angle also ensures that there is no damage to or snapping off of tube fins, regardless of the material from which they are fabricated. Furthermore, the carriage on which the nozzle beam is mounted moves at a constant speed and so allows the fouling to be removed effectively and uniformly across the heat exchange elements of the condenser. Because the fouling material is removed, air flow is no longer obstructed.

An important advantage of the automated cleaning method is that cleaning can be performed during operation while the unit is still on-line. Further, there is no need for scaffolding and labor requirements are minimized.

The automated cleaning system can be applied in three principal forms:

a. Permanently installed system complete with PLC controls, one system being supplied for each side of the condenser.

b. Semi-automatic system in which only the guide rails are permanently installed, the nozzle beam carriage being moved from section to section as the cleaning progresses.

c. Portable service unit together with a portable nozzle beam carriage and control unit. The cleaning service is performed in-house or by a qualified service provider.

IN-LEAKAGE DETECTION METHODS

In addition to effectively cleaning the condenser, the detection and repair of sources of air or water in-leakage can have an impact on plant performance and CO_2 emissions. A well known document, the EPRI Condenser In-Leakage Guideline(3), discusses in great detail the sources of both water and air in-leakage and their consequences, together with methods for their location and correction. The techniques have evolved from earlier methods (e.g. use of foam and plastic wrap), to the current *state-of-the-art* technique that involves the use of tracer gas, principally sulfur hexafluoride (SF_6). Most of the innovations were stimulated by the need to locate small circulating water in-leaks but, eventually, the same techniques became used for the location of air in-leaks as well.

Water In-leaks

The condenser is supposed to form a barrier between the cooling water - which flows between the waterboxes through the condenser tubes - and the shell side of the condenser, in which the exhaust vapor is collected as condensate. However, even small circulating water leaks will quickly find their way into the condensate, contaminating it with undesirable dissolved solids which tend to cause corrosion in the feedwater heaters, boilers or steam generators. On-line conductivity or salinity instruments are used to indicate the presence of a leak and steps should be taken to rectify the problem as soon as possible. Unfortunately, this usually means taking the unit out of service, the associated loss of revenue depending on the length of the outage. Thus the time taken to locate and correct the problem can be economically significant. This time can be reduced dramatically if the waterbox associated with the leak can be identified while the unit is still on-line.

Among the leak detection methods commonly employed in the past were smoke generators, foam or plastic wrap applied to the tubesheet, ultrasonics, tube pressure testing and membrane type rubber stoppers. These earlier techniques also left some uncertainty whether the leak was confined to only one tube; so that adjacent tubes were often plugged as well (often unnecessarily) as a form of "insurance plugging". All these methods require that the shell side of the condenser be under vacuum, provided either by the air removal system or, if the waterbox is divided, by continuing to run the unit at low load, taking each waterbox out of service in turn and checking it for leaks.

Original investigations incorporated the use of helium as a tracer gas. This not only reduced the time required to locate a leak; it also eliminated much of the former uncertainty whether the actual source of the leak had been found. However, the lowest detectible concentration of helium is one part per million above the background level, and helium was often unable to detect small water in-leaks. Thus a tracer gas with greater sensitivity was sought, and a tracer gas leak detection technique using SF_6 was developed. It was found that SF_6 in concentrations as low as one part per 10 billion (0.1ppb) can be detected, so that small leaks could now be located with confidence.

This method is illustrated in Figure 10, in which a tracer gas monitor (the Fluorotracer Analyzer™, see Figure 11), is connected to the off-gas stream leaving the air removal system. A technician is stationed at the monitor (see Figure 12, Technician at Monitor) to observe the shape of the trace on the strip chart recorder (See Figure 13), a typical response time being 30-45 seconds. Another technician is stationed in the waterbox and dispenses the tracer. The two technicians communicate through two-way sound-powered radios, chosen to avoid RF interference with other equipment.

Once the waterbox is open and the tubesheet exposed, a series of plenums is placed over a section of the tubesheet, each sized to cover an ever-smaller group of tubes. The technician in the waterbox injects the tracer gas into the plenum using a portable dispenser. Figure 14, Technician with Plenum, shows effective utilization of the Plenum for tracer gas delivery. The vacuum within the condenser allows the tracer gas to pass through any leaks that may be present and eventually appear in the off-gas stream leaving the air removal system. The technician watching the tracer gas detector monitor warns the other technician when the presence of the gas is observed. A smaller plenum is then used, and so on. By using this rigorous process of elimination, the problem tube can be rapidly identified.

Sulfur Hexafluoride can also be used on-line to identify the waterbox, even tube bundle, in which the leaking tube is located. The SF_6 is injected periodically into the circulating water before each waterbox while the unit is still on-line, and a permanently installed analyzer and monitor is used to identify the waterbox associated with the leak This reduces the time required to locate and repair the leaking tube, once the associated waterbox has been opened.

Air In-leakage

Condensers are designed to perform correctly with the unavoidable and low level of air in-leakage which is always present(4). However, greater air in-leakage than this low normal value will increase the concentration of non-condensibles in the shell side of the condenser and cause the thermal resistance to heat transfer to increase. An increase in backpressure and unit heat rate will result. The in-leakage may even rise to the point where the backpressure approaches its operating limit, forcing a reduction in load. Another effect of high air in-leakage is often an increase in the concentration of dissolved oxygen in the condensate, a concentration that will tend to increase with lower condensate temperatures. The consequences are increased corrosion of feedheaters, boilers and steam generators and/or an increase in the consumption of water treatment chemicals. Such consequences can be very complex issues involving the transport of corrosion products. Sometimes the result is accelerated corrosion in carbon steel high pressure feedwater heaters, copper alloy feedwater heaters, and excessive deposits in boiler waterwall tubes, superheaters and reheaters as well as in the steam turbine path (published work in this area is extensive). All of these consequences have a negative impact on unit profitability and performance.

Using the tracer gas technique, the source of most air in-leaks can be located with the unit still on-line. Once again, a tracer gas monitor is installed in the off-gas line from the air removal system and the technician utilizing a handheld tracer gas dispenser (see Figure 15, SF_6-Pak Hand-held Tracer Gas Dispenser) roams around the unit in a methodical manner until the technician at the monitor observes a response. The leak detection survey starts at the turbine deck level and proceeds from top to bottom of the unit, one deck at a time. Care must be taken when dispensing the tracer gas that only one potential source is sprayed at a time, otherwise the ability to associate a response with a particular source may become impaired.

THE RELATIONSHIP BETWEEN PERFORMANCE IMPROVENTS AND CO_2 EMISSION REDUCTIONS

Putman and Hornick(1) also determined a way to correlate this relationship by developing a benchmark or reference condenser duty, comparing the current operating conditions to the benchmark and then converting the difference in condenser duty or the heat loss to pounds of CO_2. A source for this reference or benchmark can be found in the analysis of turbine thermal kit data, from which a design model of the turbine LP stage can be created.

Provided that the turbogenerator is operating with the equipment configuration on which the thermal kit data was based; and that the boiler operating conditions are close to design for a given load; then the exhaust enthalpy and flow entering the condenser can be calculated as a function of load and back pressure, and these then used to estimate present condenser duty. Thus, the performance of a condenser can be compared against a calibrated and stable frame of reference, which changes only very slowly over time. Putman goes into greater detail on this matter in *Steam Surface Condensers: Basic Principles, Performance Monitoring, and Maintenance,* 2001, ASME Press, NY.

Tube fouling factors and condenser ambient heat discharges can also be quantified. The model also calculates (in MBTU/h) the excess heat discharged to the environment due to the fouling and air in-leakage of the condenser and its effect on the turbogenerator. These avoidable losses can also be readily converted to the equivalent economic loss in $/h; as well as the equivalent lbs. of excess CO_2 emissions per hour.

CO_2 Emissions Reduction Calculation

Table I displays the set of input and calculated data associated with the calculation of basic condenser performance at Big Bend, Tampa Electric (Putman and Hornick). It will be seen that the load and cooling water inlet temperature are the only two variables which have the same value in both columns. Fouling losses, from which avoidable emissions can be calculated, are the difference between the condenser duty when fouled and that estimated if the condenser were to be cleaned.

Table II shows the losses calculated after the condenser has been cleaned.

The two major fuel properties associated with the carbon dioxide emission calculation are carbon content of the fuel (weight) and fuel heating value (HV). Table III shows typical values for the three major fuels. Now 1 lb carbon produces 3.6644 lb CO_2, and, assuming a boiler combustion efficiency of 95%, the number of pounds of carbon dioxide emission (CE) per one MBtu change in condenser loss may be calculated from:

$$\mathrm{CE} = \frac{3.6644 \text{ x C x } 10^6}{0.95 \text{ x HV}}$$

$$\mathrm{CE} = \frac{3.8573 \text{ x } 10^6 \text{ x C}}{\mathrm{HV}} \qquad (1)$$

To convert the losses due to fouling or air in-leakage (MBtu/h) to equivalent carbon dioxide emission (lb_m CO_2/h), the data contained in Table III may be used with Equation (1). The last column in Table III indicates the equivalent carbon emissions per MBtu fouling loss, stated in accordance with accepted IPCC [1995](9) practice.

Consider a coal-fired unit , Big Bend, Tampa Electric (Putman and Hornick). If the rate of heat loss due to fouling is 34.968 MBtu/h, and assuming that the condenser is cleaned, then the carbon emissions if the unit is operating at this load for 8,000 hours per year will be as follows:

$$\text{Carbon Emissions} = \frac{34.968 \text{ x } 64.987 \text{ x } 8000}{2.00}$$

$$\text{Carbon Emissions} = 9.09 \text{ million pounds of carbon per year}$$

For more detailed presentation of emissions calculations please refer to Appendix A, Emissions Calculations.

ADDITIONAL CASE(s)

Australia

A significant amount of work has been done in Australia to quantify the effects of improved plant performance on reducing CO_2 emissions. The following three sets of results demonstrate the plant performance improvements and CO_2 reductions achieved through the application of the technologies described in this paper at three major power plants.

<u>Bayswater Power Station, NSW</u>

Four x 660 mw Steam Turbogenerator/black coal fired boilers.

Savings per annum/Turbogenerator unit.

- 5% improvement in condenser back-pressure
- 0.15% improvement in unit thermal efficiency
- $500,000/operational (fuel) savings
- 26,000 tonnes greenhouse gas (CO_2) reduction

Bayswater Power Station is considered the most efficient Power Generator in Australia

<u>Kwinana Power Station, WA</u>

Five x 200 mw Steam Turbo Generator/natural gas fired boilers

Savings per annum/Turbo Generator unit.

- 1.5 kpa improvements in vacuum obtained (back pressure reduced)
- 8% gain in heat transfer coefficient
- $278,000 operational (fuel savings)
- 13,329 tonnes greenhouse gas (CO_2) reduction

Wallerawang Power Station, NSW (Hovland et al (10))

Two x 500 mw Steam Turbogenerators/black coal fired boilers

Savings per annum/generator unit

- 3 to 6 kpa improvement in back pressure
- $203,731 operational (fuel) savings Unit 7
- $293,512 operational (fuel) savings Unit 8
- 2,992,380 cubic feet/day greenhouse gas (CO_2) reduction Unit 7
- 4,311,056 cubic feet/day greenhouse gas (CO_2) reduction Unit 8

Giving a combined (two unit) reduction of greenhouse gas (CO_2) emissions of 2.7 billion cu. ft. per annum

United Kingdom

Cleaning of Air Cooled Condenser (Putman and Jaresch)

To clean an air-cooled condenser installed in a 400 MW power plant located in the United Kingdom, a semi-automatic cleaning system was used. An analysis of the heat rate deviation curve for this unit showed that a 1 in.Hg improvement in turbine back pressure was equivalent to savings of $188.00/h accompanied by an increase in generation capacity of 4 MW.

Turbine back pressure before cleaning	= 3.40 in.Hg.
Turbine back pressure after cleaning	= 2.62 in.Hg.
Back pressure reduction	= 0.78 in Hg.

Savings at a 75% load factor

= 0.78 * 188.00 * 7 * 24 * 0.75 = $18,476/week

The data was taken at an ambient temperature of 59 Deg.F and it was found that the air flow before cleaning was 78% of its design flow rate.

India

Unchahar

At National Thermal Power Company of India's (NTPC) Unchahar Plant, a 200 Mw unit, a reduction in CO_2 emissions of 8000 tonnes per year was achieved through application of mechanical tube cleaning technology.

• Improvements in Vacuum	14 mm Hg
• Improvements in Heat Rate	31 kcal/kWh
• Fuel Savings	9,400 tonnes/year
• CO_2 Reductions	11,750 tonnes/year

Source: CENPEEP Performance Optimiser (Optimisation by using state-of-the-art technologies), NTPC, December, 1998.

Typical 210 Mw

The Center for Power Efficiency & Environmental Protection (CENPEEP), of National Thermal Power Company of India (NTPC), has performed air in-leakage surveys and reports these savings as a result of a reduction of air in-leakage on a typical 210 Mw unit.

• Improvement in Vacuum	7.2 mm Hg
• Improvement in Heat Rate	16.0 kcal/kWh
• Fuel Saving	6,400 tonnes/year
• CO_2 Reduction	8,000 tonnes/year

Source: CENPEEP Performance Optimiser (Optimisation by using *state-of-the-art* technologies), NTPC, March, 2001.

CONCLUSION

Improvements in power plant performance and reductions in CO_2 emissions through the application of *state-of-the-art* technologies for condenser cleaning and air in-leakage detection are achievable. This paper demonstrates the correlation between improved condenser performance and a reduction in CO_2 emissions. When cleaning the condenser it is imperative to select the most effective method, yielding the best results. Literally, tons of emissions have been avoided due to the implementation of these sound practices. The technology is available for deployment.

ACKNOWLEDGEMENTS

The authors acknowledge Richard E. Putman for his prior work in equating changes in condenser performance to reductions in CO_2 emissions, as published in his book; *Steam Surface Condensers: Basic Principles, Performance Monitoring, and Maintenance* and to the introduction of mechanical tube cleaning and air in-leakage detection methods as "proper maintenance" in his paper *Proper Maintenance Practices Involving Condenser Cleaning and Air In-leakage Inspection* delivered at Oxford University in England, upon which most of this work has been based.

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Figure 1.0

Type C3S Tube Cleaner

Figure 2.0

Type C4S Tube Cleaner

Figure 3.0
Water Gun

Figure 4.0
Portable Booster Pump

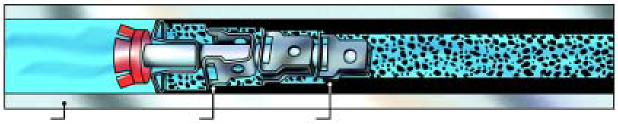

Figure 5.0
C4S Tube Cleaner in Action

Figure 6.0
Hex Cleaner

Figure 7.0
Cal Buster

Figure 8.0
Stainless Steel Tube Cleaning Brush

Figure 9.0
Semi-Automated System

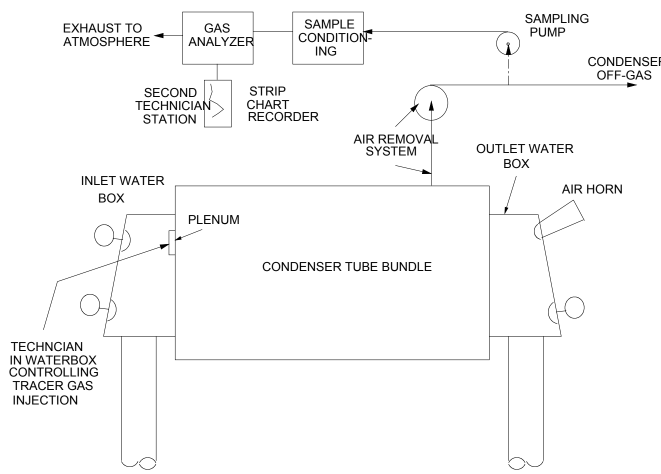

Figure 10.0
General setup for tube water leak test

Figure 11
The Fluorotracer Analyzer™

Figure 12
Technician at Monitor

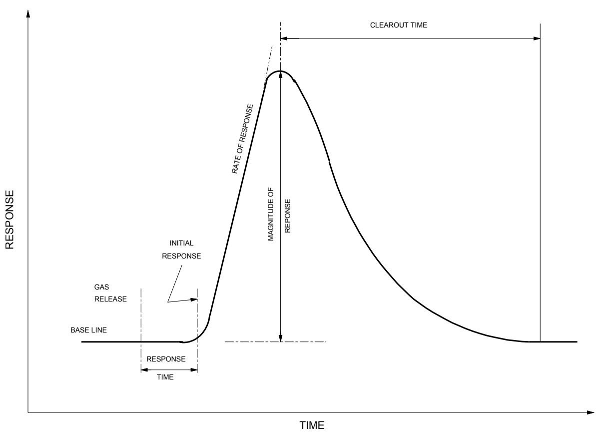

Figure 13
Chart Recording of a typical leak response

Figure 14
Technician with Plenum

Figure 15
SF6-Pak Hand-held Tracer Gas Dispenser

Generator Load		**=398.941 MW**	
Fouling Losses		**=34.968MBTU/h**	
		PRESENT CONDITIONS	CLEAN CONDITIONS
C.W. Flow	=	228258.700	249200.000 GPM
Condenser Duty	=	1838.382	1803.414 MBTU/h
Exhaust Flow	=	1810.699	1782.084 Klb/h
Inlet Temperature	=	90.570	90.570 Deg F
Outlet Temperature	A =	107.022	105.358 Deg F
Steam Temperature	A =	123.950	115.946 Deg F
Back Pressure	A =	3.844	3.077 in Hg
Outlet Temperature	B =	107.031	105.357 Deg F
Steam Temperature	B =	124.180	115.943 Deg F
Back Pressure	B =	3.868	3.077 in HG

Table I
Condenser Performance Calculations

Condenser Losses in MBTU/h		
Generator Load	=	398.941 MW
Total Losses	=	34.968 MBTU/h

Table II
Total Losses in MBTU/h

Fuel	C, lb/lb/fuel	HV, Btu/lb_m	lb_m CO_2/ MBtu Loss	lb_m Carbon/ MBtu Loss
Bituminous coal	0.860	13,930	238.1	64.987
Fuel oil	0.863	18,558	179.4	48.950
Natural gas	0.749	25,128	115.0	31.376

Table III
Carbon Dioxide Emissions, lb_m CO_2 per MBTU Losses
(Source: Putman, R.E., 2001, Steam Surface Condensers)

APPENDIX A
Emissions Calculations

Table A.1 below gives some of then basic data that should be known for the fuel being fired to the boiler of the turbogenerator unit under investigation:

Fuel	1 C	2 HV	3 CO_2/MBTU	4 C/MBTU
Bituminous Coal	0.860	13,930	238.1	64.987
Fuel Oil	0.863	18,558	179.4	48.950
Natural Gas	0.749	25,128	115.0	31.376

Table A.1
Some Properties of Fuels

Definitions

C	=	carbon content of fuel	lb carbon/lb. fuel
HV	=	fuel heating value	BTU/lb_m
CO_2/MBTU	=	weight of carbon dioxide per MBTU loss	lb_m/MBTU
C/MBTU	=	weight of carbon per MBTU loss	lb_m/MBTU
CO_2/C	=	weight of carbon dioxide per lb. carbon	lb/lb
	=	3.6644 lb CO_2 per lb. carbon	
CE	=	carbon dioxide emissions per year due to fouling	lb/year
$/MBTU	=	fuel energy cost	$/MBTU
LOSS	=	condenser avoidable loss due to fouling	MBTU/h

Assuming a boiler combustion efficiency of 96%, then the weight of carbon dioxide emitted per 1 million BTU of avoidable condenser loss may be calculated from:

$$CO2/MBTU = \frac{3.6644 * C * 1.0E+06}{0.95 * HV} \quad \text{(A.1)}$$

Similarly, the weight of carbon emission equivalent to CO_2/MBTU may be calculated from:

$$C/MBTU = \frac{C * 1.0E+06}{0.95 * HV} \quad \text{(A.2)}$$

It has been our practice to estimate the avoidable condenser losses due to fouling in MBTU/hour units. Assume a condenser with an avoidable loss (LOSS) of 34.968 MBTU/h and that, after cleaning, fouling resumes at a linear rate and that there are 8000 operating hours per year, then:

$$CE = \frac{LOSS * CO2/MBTU * 8000}{2} \quad \text{(A.3)}$$

or,

CE = 34.968 * 238.1 * 8000 / (2 * 1.0e+06)
= 33.3 million lb CO_2 / year

Occasionally, the avoidable losses are stated in some other units, e.g. as $/week. In this case, the following should be used to compute the equivalent carbon dioxide emissions per year:

$$CE = \frac{LOSS * 52 * CO2/MBTU * 8000}{\$/MBTU * 2} \quad \text{(A.4)}$$

Sometimes the fuel cost is stated in $/short ton ($/TON), not as $/MBTU. In such cases, $/MBTU may be calculated from the following:

$$\$/MBTU = \frac{\$/TON * 1.0e+06}{2000 * HV} \quad \text{(A.5)}$$