Evaluation of Techniques for Detecting Small Condenser Tube Leaks

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ABSTRACT

Condenser cooling water inleakage can result in huge costs for power plants as a result of plant derates and outages to locate and mitigate leaks, vendor services to help with leak location detection, or extended plant outages necessitated to address catastrophic inleakage. In order for some plants to maintain optimal secondary water chemistry they need the ability to detect leak flow rates as low as 1–2 gallons (3.8–7.6 liters) per day.

Although many of the presently available inspection and monitoring technologies are capable of detecting leaks of this magnitude when they are conducted under optimum conditions, the basic inspection practices have not changed in nearly 30 years, and existing inspection technologies have been pushed to their practical detection limits under the present inspection procedures. This report provides a summary of the present condenser tube inspection and leak detection practices and their leak detection sensitivity (either qualitative or quantitative), based on an industry review of the current best practices.

Keywords
Condenser tube inspection
Leak rate testing
Nuclear power plant
Steam condenser
Tube leak

EXECUTIVE SUMMARY

The condenser is regarded as the point in the plant water-steam cycle where the system thermal efficiency is largely determined. It serves to condense turbine exhaust steam in order to create a vacuum at the exhaust flange and to recycle the exhaust steam for reuse in the plant circulating loop. As condensers age, the condenser tubes inevitably suffer a variety of damage modes that lead to the degradation of the tube walls, which will eventually lead to tube leaks. Left unchecked, the chemical contamination caused by these leaks will eventually result in serious damage to the various plant components.

Condenser cooling water inleakage can result in huge costs for power plants as a result of plant derates and outages to locate and mitigate leaks, vendor services to help with leak location detection, or extended plant outages necessitated to address catastrophic inleakage. In order for some plants to maintain optimal secondary water chemistry they need the ability to detect leak flow rates as low as 1–2 gallons per day. In order to achieve this detection target, operating plants may need to consider modifying their maintenance and inspection guidelines to include new or underutilized inspection approaches.

An industry review was conducted to determine the capabilities of the present condenser tube inspection practices. In this study, a list of condenser tube inspection technologies was compiled, and information on each technology was collected through a process of literature review, product search, and survey of industry professionals. Each inspection technology was qualitatively evaluated using a series of metrics. The most critical method is the leak detection sensitivity, which is defined in terms of leak rate (or leak power), with units of mbar*L/s. This convention is favored by the industry over the simpler volume flow rate because leak power serves as a better description of detection sensitivity for technologies that operate in a range of environmental conditions. To detect leaks on the order of 1 gallon per day, a candidate technology should have a leak detection sensitivity of roughly 10^{-2} mbar*L/s or better.

The study revealed that the power generating industry has espoused a proactive plan of preventive inspection and maintenance, whereas in the past, leak detection and equipment repair was often reactionary. As a result, the inspection industry has favored technologies designed to characterize tube damage over technology that is designed to detect and locate existing leaks. Plant operators rely on three categories of inspection and monitoring technology:

- Technologies that identify and characterize tube damage that may lead to leakage
- Online monitors that provide plant operators with evidence of the onset of leakage
- Technologies that can detect and locate leaking tubes

Although each operating plant may rely on different combinations of specific inspection technologies, the sequence of inspections follows a common pattern. Plant operators first rely on preventive inspection and damage characterization of the condenser tubes. The commercially available inspection methods include:

- Visual inspection – tubesheet inspection, internal inspection, and video probe inspection
- Eddy current inspection – traditional eddy current and remote field eddy current
- Internal rotary inspection system (IRIS)

- Guided wave testing – ultrasonic guided wave and acoustic pulse reflectometry

Of these methods, eddy current testing is the most widely accepted method for inspecting tubes and for generating records of tube condition, followed by visual inspection.

In the event that a tube failure does occur, the water chemistry monitors installed within the plant circulating loop usually provide the first indication of cooling water inleakage. Once leakage is detected, inspectors may use one of several commercially available leak detection methods to identify and locate the leaking tube. These methods and sensitivity include:

- Tube drip testing – 10^{-2} mbar*L/s
- Hydrostatic fill testing – $5x10^{-3}$ mbar*L/s
- Tube pressure decay test – 10^{-2} mbar*L/s
- Soap or foam testing – 10^{-2} mbar*L/s
- Dimple plug testing – 10^{-2} mbar*L/s
- Acoustic leak detection – 10^{-2} mbar*L/s
- Tracer gas detection method – 10^{-5} mbar*L/s
- Radioactive tracer detection method – 10^{-6} mbar*L/s

In addition to these detection methods, there are also some experimental leak detection methods that are currently undergoing field testing.

Based on the responses of plant operators and the defined target leak detection sensitivity defined in this study, the list of the current inspection practices appears to meet the current industry needs, but only under the best inspection conditions. In the actual inspection conditions of the plant, unexpected noise conditions or complications to the inspection procedure often reduce the effective detection sensitivity. Although all of these technologies are capable of detecting 1 gallon per day leaks, industry professionals have indicated that the realistic leak detection capabilities for the more basic techniques tend to be less sensitive, perhaps 10 gallons per day. Many of these techniques are also quite costly to implement with respect to labor and time requirements.

Although many of the commercially available leak detection techniques have seen improvements over the past decade or so, the basic inspection practices have not changed significantly in the past 30 years. If plant operators and industry regulators determine that condensers must be screened more extensively for leaks on the order of 1 gallon per day, then there may be a need for further development in the industry's leak detection capabilities. Developing new technology may be considered in the future to improve leak detection sensitivity and inspection speed and to reduce inspection costs.

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INTRODUCTION

The condenser is regarded as the point in the plant water-steam cycle where the system thermal efficiency is largely determined. The condenser serves to condense the exhaust steam that exits the low pressure turbine in order to create a vacuum at the exhaust flange and to recycle the exhaust steam for reuse in the steam-water cycle. By condensing the exhaust steam in a vacuum, the energy transfer from the steam to the turbine is maximized, resulting in a lower overall heat rate for the plant. The condenser is also the most likely point in the plant cycle for the condensate/feedwater to become contaminated. To operate, the condenser draws cooling water from an external source such as a lake, river, or the sea, and passes the cooling water through a series of tubes. The condenser tubes and tubesheets act as barriers between the highly purified condensate/feedwater of the plant and the relatively contaminated cooling water. Due to the vacuum inside the condenser, any water leakage from the condenser tube will contaminate the condensate/feedwater, which will lead to increased corrosion of plant systems.

As condensers age, the condenser tubes inevitably suffer a variety of damage modes such as mechanical fatigue, turbulent water erosion, microbial fouling, thermal scaling, and chemical corrosion that lead to the degradation of the tube walls, which will eventually cause the formation of tube leaks. Left unchecked, leaks will eventually cause serious damage to the piping, steam generators (or fired boilers), feedwater heaters, and turbines. The required response times for such leakage events are generally short and are governed by the chemical composition of the cooling water and the rate of cooling water contamination. If a serious leak is allowed to persist, then in addition to the damage to the plant flow loop components, the plant will also experience a reduction in its operating life and a reduction in the overall efficiency.

The inspection guidelines defined by the operating and maintenance programs at all power plants require some level of periodic inspection of the condensers. Each plant has its own operating guidelines for inspection and maintenance and response to a detected in-leakage event. These guidelines are developed on a basis of anticipated damage modes to the condenser, analysis of the cooling water chemistry, and prior damage history. For example, plants using seawater as their source of circulating water will be more sensitive to sulphide induced corrosion than plants operating using lake water.

Most operating plants require some minimal level of screening for all condenser tubes and a more thorough examination of at least 10% to 20% of the tubes during each outage. In this fashion, all tubes within the condenser will be screened for damage over a period of several years. An industry target of zero leakage tolerance is espoused by almost all plant maintenance managers. To achieve this target, plant managers have adopted a philosophy of preventative maintenance and inspection, where tubes at risk of leakage are identified before they lose their integrity and removed from service. As a result, the non-destructive evaluation industry has emphasized condenser inspection technologies that are capable of identifying wall thinning and other forms of tube wear over technologies focused on the detection of actual leakage events. In most cases, this inspection approach has been successful for the industry, but incidences of tube leakage not detected by these methods have occurred. In cases where very small tube leaks are present in the condenser, the most common industry tools for tube inspection have had difficulty identifying the source flaw, and more specific inspection technologies have been needed. In the past, due to the economic cost considerations of removing a plant from operation long enough to conduct intensive inspections, many plants have settled for leak detection thresholds on the order of 50 to 100 gallons a day.

Cooling water inleakage can result in huge costs for power plants as a result of plant derates and outages to locate and mitigate leaks, vendor services to help with leak location detection, or extended plant outages necessitated to address catastrophic inleakage. In order for some plants to maintain optimal secondary water chemistry they need the ability to detect leak flow rates as low as 1 to 2 gallons per day. In order to achieve this detection target, operating plants may need to consider modifying their maintenance and inspection guidelines to include new or underutilized inspection approaches.

This report attempts to summarize the condenser tube inspection technologies that are either commercially available to the industry or presently undergoing experimental field trials. Although this report will attempt to cover most of the common inspection technologies, emphasis is placed on technologies that demonstrate the capability of detecting a target leak flow rate of 1 to 2 gallons per day. In addition to the technology's detection sensitivity, each technology is also evaluated based on a series of qualitative metrics to determine the suitability of the technology for field service. The results of these evaluations are summarized to provide an evaluation of the power generation industry's currently accepted leak detection threshold and to determine the target detection thresholds that may be achieved in the near future.

Engineering Units

Conversion factors for engineering units used in this project are provided in Table 1-1 for reference.

Table 1-1
Unit Conversions

Parameter	U.S. Customary Unit	SI Unit	Conversion Equation
area	ft^2	m^2	$1\ ft^2 = 0.0929 m^2$
linear dimension	foot	meter	1 foot = 0.3048 meter
temperature	°F	°C	1 °F = 1.8 * °C + 32
pressure	inches Hg	kPa	1 inHg = 3.386 kPa
pressure	psi	kPa	1 psi = 6.895 kPa
pressure	bar	Pa	1 bar = 1 Pa
mass flow	lb_m/hr	kg/s	$1\ lb_m/hr = 0.000126\ kg/s$
volume	ft^3	m^3	$1\ ft^3 = 0.0283\ m^3$
volume	gallon	L	1 gallon = 3.785 L
volumetric flow	ft^3/min	m^3/s	$1\ ft^3/min = 0.000472\ m^3/s$

2

DEFINITION OF A POWER PLANT CONDENSER

The primary two purposes of the condenser is to create a vacuum at the exhaust of the low pressure turbine by condensing steam and to recycle the exhaust steam from the turbine for reuse in the steam-water cycle. By condensing the exhaust steam at a vacuum, the energy transfer from the steam to the turbine is maximized, resulting in a lower overall heat rate for the plant. In addition to these primary functions, the condenser also serves to:

- provide a closed space for the turbine exhaust steam to collect and release its latent heat of vaporization to the cooling water,
- serve as a collection point for secondary steam cycle and water cycle bleed-off,
- act as a heat dump for support flows,
- act as a mixing location for additional feedwater makeup and some of the water chemical treatment,
- and remove non-condensable gasses from steam-water cycle.

The condenser steam inlet is connected directly to the low pressure turbine exhaust. Much like the turbine, there is generally no backup unit for condenser. If the performance of the condenser is reduced, then the overall efficiency of the plant diminishes. Furthermore, if significant maintenance of the condenser is required, then the plant must be brought offline. Therefore, great care must be taken to ensure that the condenser is operating efficiently.

The condenser is the collection point for all secondary cycle steam and water flows, after which they are pumped in combination through the feedwater system to ultimately be boiled for re-use and expansion in the turbine. Contamination occurring in the steam side of the condenser has a direct path to the downstream steam generation equipment.

Overview of Surface Condenser Design

A surface condenser is a specialized type of shell-and-tube heat exchanger. All surface condensers rely on the circulation of cooling water to remove heat from the steam, permitting the steam to condense into water and providing a low backpressure for the turbine. To accomplish this, cooling water is drawn from a heat sink (natural body of water or cooling tower) into a chamber called a waterbox where it flows into a series of parallel tubes numbering in the low tens of thousands. As the cooling water flows through these tubes, exhaust steam from the low pressure turbine enters the condenser shell and passes over the tubes. When exiting the turbine, the exhaust steam may reach peak velocities approaching 150 m/s. Heat is withdrawn from the steam into the cooling water through the tube walls, and the steam condenses into liquid water. To achieve adequate cooling, the cooling water mass flow rate through the tubes is usually 50 to 100 times the mass flow rate of the exhaust steam. The steam once condensed collects at the bottom chamber of the condenser, known as the hotwell, where it leaves the condenser to be recycled back to the plant steam generation system. A common surface condenser design is shown in Figure 2-1.

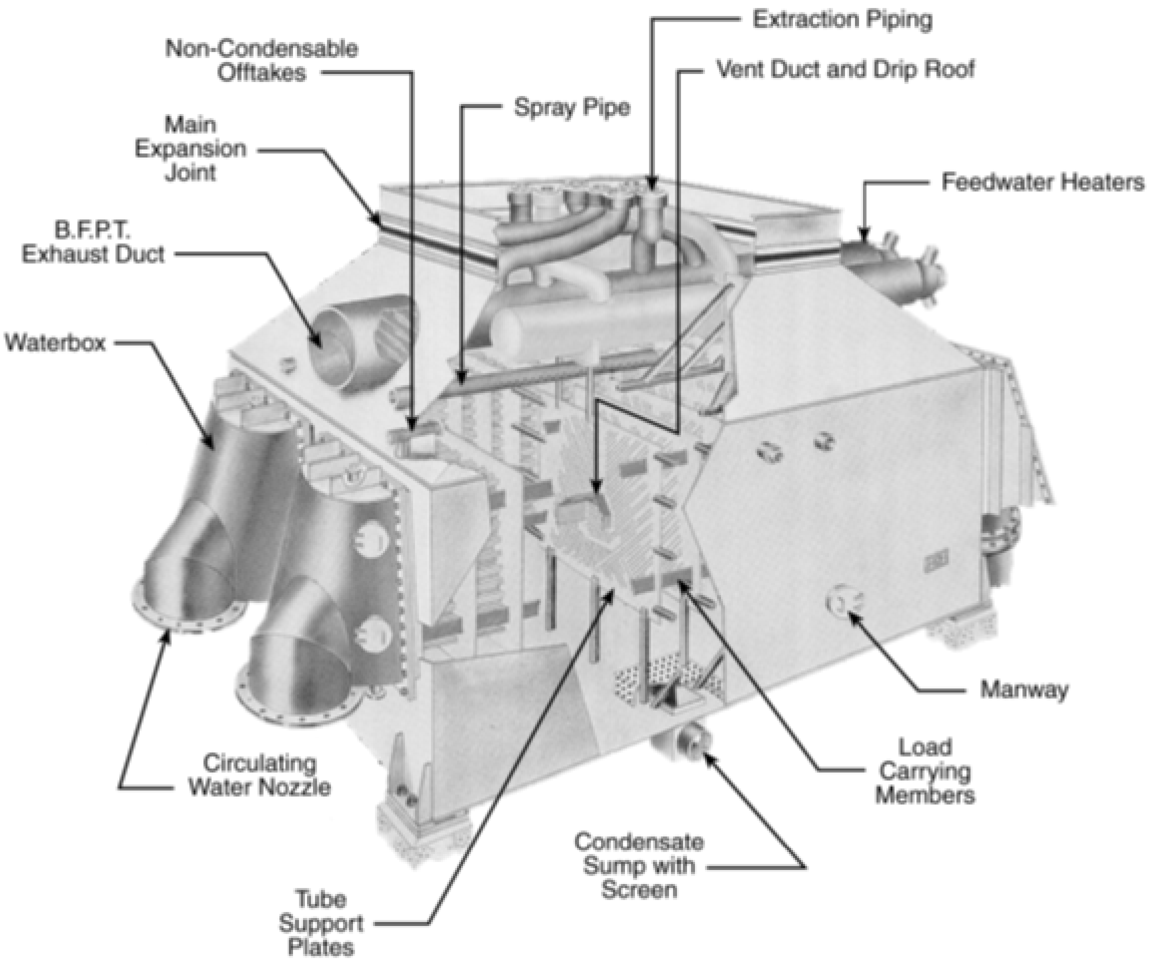

Figure 2-1
Illustration of a Typical Surface Condenser Design

Although surface condenser designs vary significantly based on plant load and type, all surface condensers include certain critical elements. The common components are discussed below.

- Shell – The shell serves as the condenser enclosure and the containment vessel for the turbine exhaust steam. The shell is usually composed of carbon steel or stainless steel, and must be designed to withstand the vacuum conditions of the condenser. The shell is designed to withstand a vacuum approaching 1 atmosphere. Therefore, surface condensers are not governed by the ASME Pressure Vessel Code, but instead by standards defined by the Heat Exchange Institute (HEI).
- Turbine Exhaust Connection – The turbine exhaust serves as an air-tight connection between the low pressure turbine exhaust and the condenser. This connection usually includes an expansion joint to accommodate for thermal expansion and contraction.
- Tubes – The tubes serve as the transport structure for the cooling water, as a leak-tight barrier between the cooling water and the steam, and as the heat transfer surface between the two fluids.
- Waterbox – The waterbox serves as a transition piece for cooling water to either enter or exit the condenser tubes. The number and arrangement of the waterboxes on the condenser

depends heavily on the condenser design. The waterbox can be composed of a wide range of materials, including carbon steel, cast iron, copper alloys, or titanium. In some condensers, the waterboxes are designed to be removed from the condenser to provide unobstructed access to the tubesheet.

- Tubesheet – The tubesheet is a semi-rigid metal plate that includes a pattern of holes that match the arrangement of the tubes within the tube bundle. The ends of the tubes are joined to the tubesheet to form a leak-proof seal between the waterbox and the interior of the condenser shell.
- Tube Support Plates and Load Members – A support structure composed primarily of tube support plates and load members are included within the condenser shell to support the weight of the tube bundles. The tube support plates mirror the construction of the tubesheets; they are metal plates with a series of holes that the tubes within the tube bundle pass through. The support plates serve to prevent tube sagging through the condenser shell and to prevent excessive tube vibration. In some cases, they also serve as steam guides to improve the heat transfer efficiency of the condenser. The support plates are in turn supported by load members that are attached to a frame within the condenser shell or to the shell itself.
- Hotwell – The hotwell serves as the water collection reservoir for the condensate. It is constructed with the same material as the shell, and is usually sized to contain all condensate that the condenser would generate during a 1 minute period of peak capacity.
- Non-Condensable Off-gas Lines –The purpose of the off-gas lines is to collect all of the non-condensable gasses (dissolved Oxygen, Nitrogen, Carbon Dioxide, etc.) that leaks into the steam flow lines throughout the plant and evacuate them from the steam. Non-condensable gas has a tendency to flow to the coldest areas of the condenser, namely the circulating water inlet regions and the center of the tube bundles. A collection pipe usually runs along the central open cavity of each condenser tube bundle. These pipes are connected to either steam jet air ejectors or evacuation pumps located outside of the condenser, which draw the non-condensable gasses from the off-gas lines.
- Manways – Multiple leak-tight manways are included at several locations throughout the condenser to permit access to the various condenser components. Generally, there are several manways located in hotwell, in each waterbox, and in the condenser shell.

Many additional components may be included within the condenser depending on the requirements of the plant.

The overall configuration of the condenser can be defined by a few over-arching characteristics. In terms of inspection, these characteristics are important because they impose restrictions on the inspection methods that can be used. The relevant characteristics are outlined below.

- Round or Square – The condenser can be constructed with either a cylindrically-shaped shell or with a box-like shell. Cylindrically shaped condensers are typically used only for smaller plants. Generally, the tube configurations are more compact and provide less room for access on the steam side of the condenser. Square condensers tend to be much larger and provide much more room for internal access. These condensers are also more complex in design and may include secondary features such as a greater number of tube bundles, and embedded feedwater heaters.

- Side Mounted or Vertically Mounted – The industry preference is to mount the condenser directly underneath the low pressure turbine and the associated turbine deck (vertically mounted). In some cases, the condenser is side-mounted for space considerations and to accommodate secondary flow line connections.
- Single-Pass or Two-Pass – In a single pass condenser, the cooling water flows into the waterbox(es) on one side, through the condenser tubes, and are collected by the waterbox(es) on the opposite side. In a two-pass condenser, the water enters the condenser on one side and passes through to the transition or turn-around water box on the far side. From the far side, it re-enters the condenser and passes through in the opposite direction, where it leaves the condenser system. Since the inlet and eixt of the cooling water flow occurs on the same end, those water boxes contain a divider plate to ensure no mixing or recirculation of the warm and cold cooling water flows.
- Single Compartment or Multi-Compartment – Most condensers include more than one set of water boxes. In a multi-compartment condenser, there are multiple pairs of waterboxes that are each attached to some fraction of the entire tube sheet. In a multi-compartment condenser, it is possible to remove one pair of water boxes (one on either side of the condenser) and operate the condenser under a partial load. In this configuration, it is possible to access some of the condenser tubes while the steam side of the condenser remains under vacuum. In a single compartment condenser, all tubes in the tubesheet are connected to a single set of waterboxes. To access the tubes the entire condenser must be taken offline.

Note that there are many other major factors that affect the overall configuration of the condenser, but the remaining factors are less relevant to the inspection approach. For additional information regarding the composition of surface condensers, refer to EPRI Report 1003088, “Condenser Application and Maintenance Guide.”

Additional Information Regarding Condenser Tubes

The condenser tubes serve three basic roles – as the transport structure for the cooling water, as the primary heat transfer surface between the cooling fluid and the steam, and as a leak-tight barrier between the two fluids. The engineering decisions used to choose the design of the tubes within the condenser must balance the requirements of these roles and must also consider any additional requirements imposed by the other components in the circulating water loop as wells as the plant environmental conditions. These factors are used to select the tube materials, tube geometries, and the arrangement of the tube bundles within the condenser.

The most common design uses straight, single diameter tubes found within single pass condensers. These tubes are circular with a single fixed outer diameter and inner diameter. More recently, condenser designers have experimented with the use of twisted or spiral tubes. These tubes have an elliptical profile, where the major axis of the ellipse is rotated down the axis of the tube to form a natural twist. The tube twist creates turbulence and allows for greater heat transfer surface area along each tube while still maintaining the same fluid flow rate.

Tube materials vary based on the operating requirements of the condenser. Materials such as Aluminum and Aluminum alloys, Brass, Copper, Nickel alloys, Stainless Steel, Titanium, Bronze, and more complex metal alloys have been used for the condenser tubes. For high heat transfer, it is desirable to use thin-walled tubes composed of materials with high thermal conductivity. To ensure the operation of the tube as a leak-tight barrier, it is desirable to have thicker tube walls composed of materials that are resistant to many forms of corrosion and erosion. Other factors, such as the desired cooling water flow rate, will also affect the design considerations for the tubes. Most of the high conductivity materials (such as copper and admiralty brass) are more sensitivity to corrosion, whereas the most corrosion resistant materials have (titanium, stainless steel) have poorer thermal conductivity.

Damage Mechanisms for Condenser Tubes

The following damage mechanisms are common concerns for condenser tubes.

- In older condenser models, manufacturing flaws produced by inconsistent tube manufacturing techniques produced defects within the tube walls that served as seed points for corrosion. Cracking at the tube-to-tubesheet interface due to damage during assembly has also been an issue. Stresses induced in the tubes when they are flared within the tubesheet can lead to circumferential cracks just inside the tubesheet. Over time, the manufacturing quality of tubes has improved, and the number of tube failures related to this cause has diminished.
- Tube inlet erosion occurs as turbulent cooling water enters the tube from the water box. The effect of the turbulence causes damage to the first few tube diameters of the tubes over time. In some plants, inserts have been added to the tube inlets to smooth water entry and reduce turbulence.
- Tube fretting and vibration produces mechanical damage to the outer wall. This kind of damage most typically occurs at the support plates, but vibration damage has been noted between adjacent tubes when tube sagging occurs. In other cases, foreign objects have been found lodged within condensers and have been known to puncture tube walls. Finally, if tube vibration is allowed to persist for a significant amount of time, then the tubes will begin to suffer fatigue cracking.
- Stress corrosion cracking (SCC) of the tubes can manifest on either the outside or inside diameter. In general, SCC occurs when localized corrosion within a high stress region on the tube lead to sudden onset of cracking. SCC on the inside diameter generally occurs due to a rise in stress within the tube wall. This occurs when the tube becomes dented due to physical impact or due to external pressure. The most common cause is when the tube support plates suffer general corrosion, which can lead to material expansion (corrosion product buildup) around the tubes. The increased pressure on the tube walls then makes the tube more susceptible to stress corrosion at these points. SCC on the tube outside diameter is subject to a wider range of conditions, but in general is related to either tube deformation or thermal stresses.
- Gradual tube corrosion is the most prevalent form of tube failure and can take many forms. General corrosion occurs on the tube inner diameters as the largely untreated cooling water flows through the tubes over long periods of time. General corrosion leads to even thinning of the tube walls. Pitting corrosion occurs when there is a local perturbation of fluid flow either within the tube or on the tube outside surface. One example cause of flow perturbation is the formation of deposits on the tube surface.
- Wet steam impingement on the tube outer diameters, especially in steam bypass areas, can produce regions of heavy erosion. Rapid degradation of the tube outer diameter due to the development of wet droplet high velocity flow regimes is a significant problem due to the relatively short reaction times afforded by the failure mechanism. This damage occurs on the

sides of tubes facing the flow direction. In early stages, it takes the form of polishing, but often leads to perforation of the tube walls.

- Sulphide attack of copper tubes is common in cases where seawater is used as the cooling fluid. The presence of high concentrations of sulphide in the cooling water will increase the rate of pitting corrosion and may encourage the growth of deposits on the tube wall.
- Copper tubes are also susceptible to condensate grooving in areas of the condenser that are subjected to high concentrations of ammonia and oxygen, such as within non-condensable gas collection regions of the tube bundles. Ammonia grooving is often marked by distinctive circumferential patterns on the tube outer diameters, but can ultimately lead to general tube wall loss and through-wall leaks.
- Microbial induced corrosion occurs when biological elements such as bacteria, biofilms, algae, or small marine organisms come in contact with the tube sheets and tube surfaces. Biological agents contained in these substances will react with the metal surface to produce rapid pitting of the tube surfaces. The presence of these elements in the condenser also accelerates the accumulation of biofouling material
- In cases where the tubes and tubesheets are composed of different metals, galvanic corrosion may begin to affect the joints at the tube entrances. Under this condition, the tubes themselves are rarely susceptible to damage, but leaks may form at the tubesheet.
- Tube damage has also been caused by both overly aggressive mechanical and chemical cleaning techniques. Mechanical damage caused by the misapplication of tube cleaning tools can leave striations in the tube walls. Chemical damage can be caused by either using an excessive amount of cleaning solvent or by inadequately flushing the solvent from the tubes after cleaning. In both cases, the excess solvent may attack the bare metal of the tube walls, which may either encourage other types of corrosion or cause the formation of deposits.
- Over time, the high heat rates through the tube walls can lead to tube scaling, which results in a temporary or most long-lasting coating on the tube inner diameter. The presence of tube scaling will eventually lead to increased general corrosion, pitting corrosion, and fouling.

In addition to these damage mechanisms, tube fouling eventually occurs. Fouling is most often considered a tube interior concern. It consists of a buildup of undesirable particulate matter on the tube wall, which reduces heat transfer efficiency. This can ultimately lead to partial or complete tube obstruction. Generally, fouling is only related to leakage when corrosion fouling occurs, where corrosion buildup occurs downstream from a wearing region of the tube. In many cases, tube fouling increases the complication of inspecting the tubes by reducing direct access to the tube wall by inspection tools. As a result, tube inspection is often paired with tube cleaning.

3

LEAK RATE MEASUREMENT CONVENTION

The presence of a leak naturally implies that an unintended crack, hole, or porosity exists in the structure. Ideally, for a given set of conditions, an operator would like to be able to associate a measurable volume flow rate through the penetration to the physical size of the leak. In actuality this relation is highly dependent on the conditions under which the leak occurs. Factors such as the size and shape of the leak, the composition and temperature of the leaking fluid, the pressure differential across the leak, and the geometry of the leaking structure all affect the leak rate. As a consequence, there is no direct relation between the size of a leak and the flow rate through the leak.

Instead, a standard definition of leak rate has been developed that can be applied to a wide range of leaking conditions. Leak rate is defined by the standard Equation 3-1,

$$\boldsymbol{Q} = \frac{\boldsymbol{\Delta(\mathrm{PV})}}{\boldsymbol{\Delta \mathrm{t}}} \qquad \textbf{Eq. 3-1}$$

Where:

Q is the leak rate,
P is the pressure differential across the leak,
V is the enclosed volume, and
t is the time.

Typically, leak rate is reported in units of mbarL/sec (or in m^3Pa/s). Conveniently, the equivalent unit of leak rate is Watts, so Equation 3-1 literally describes the power of the leak.

Leak rate can either be interpreted as the amount of fluid (V) that must be removed from a fixed volume to produce a given pressure decrease in a set time ($\Delta P/\Delta t$), or as the necessary volume flow rate ($\Delta V/\Delta t$) required to produce a given pressure differential (P) across a barrier. Using this definition, an approximate comparison of leak rates can be made across a wide range of test conditions. Under this definition a common metric is available for comparing a wide array of leak magnitudes and detection sensitivities. Commonly accepted detection ranges for leak rate are summarized in Table 3-1.

Table 3-1
Standard Leak Rate Ranges for Helium at Room Temperature

Leak Criterion	**Leak Rate (mbarL/s)**	**Flow Regime**	**Comment**
Coarse Leak	$>10^{-2}$	Turbulent / Laminar	A steady leak is visibly observable
Vapor-Tight	$< 10^{-3}$	Laminar	Limited or no leakage of water vapor
Oil-Tight	$< 10^{-5}$	Laminar / Transitional	Limited or no leakage of very low viscosity fluids
Gas-Tight	$< 10^{-7}$	Transitional	Limited or no leakage of a gas
Absolutely Tight	$< 10^{-10}$	Molecular	Essentially no leakage detectable
Diffusion Limit	$< 10^{-12}$	Molecular	Leakage only possible by diffusion through inter-granular boundaries of material

If the leak rate is measured, it is possible to loosely estimate the physical size of a leak under a given set of assumptions with the Hagen-Poiseuille equation (Equation 3-2)

$$\Delta P = \frac{128\mu L\dot{q}}{\pi d^4} \qquad \textbf{Eq. 3-2}$$

Where:

μ is the dynamic viscosity of the fluid (~10^-3 sPa for water at room temperature),
L is the flow length of the leak,
q is the volumetric flow rate of the fluid, and
d is the diameter of a circular leak.

This approach to estimating leak size assumes that the leak cross-section is roughly circular, that the leak is large enough to support consistent fluid flow, and that the length of the hole is sufficiently long to permit a laminar flow regime. Using Equation 3-2, it is possible to make a rough estimation of a typical target flaw size for this investigation. Although the actual size of a flaw is not directly relevant to the plant operators, there are many inspection technologies whose sensitivity is directly dependent on the dimensions of the flaw. Therefore, it is important to establish the approximate magnitude of the flaw aperture for the leak rate targeted in this investigation.

Assume that a pin-hole leak has formed in a tube with a 1.5 mm wall. Also assume that the outside pressure of the tube is at a relatively moderate vacuum of 100 mbar (91170 Pa differential pressure). In this investigation, the target detectable flow rate is 1 gallon/day or approximately 4.38x10^{-5} L/s. The critical flaw diameter can then be calculated as

$$d = \left(\frac{128(10^{-3}sPa)(0.0015m)(4.4x10^{-8}m^3/s)}{\pi(91170Pa)}\right)^{1/4} \cong 74\mu m$$

or approximately 0.003 inch in diameter. The equivalent leak rate for a hole of this diameter is calculated to be on the order of 4x10^{-2} mbarL/s, which falls within the coarse leak criterion.

Based on the measured leak rate, it is possible to estimate the rate that contaminants are entering the water-steam cycle, which is the metric of real interest to the plant operators. This estimation is highly dependent on the source of the condenser cooling water. For example, plants using seawater as their source for circulating water see very large chemistry changes in the condensate for very small leaks. For a similar plant using a relatively pure freshwater cooling source, it may be possible to tolerate leaks that are an order of magnitude larger. Ultimately, each plant must evaluate the magnitude of the leak that it can tolerate.

4

EVALUATION METRICS FOR INSPECTION METHODS

A list of condenser tube inspection technologies that are in current use have been provided in Section 5 of this report. The majority of the listed technologies are currently in widespread use throughout the industry. Some of the listed technologies are either in different stages of development field trials, and some are technologies that have been overshadowed by better performing inspection methods, but have been included due to their persistence within the industry. Information on each technology was collected through a process of literature review, product search, and survey of industry professionals. As the information on each technology was compiled, a series of metrics were used to qualitatively evaluate the effectiveness of the inspection method in terms of its detection capabilities and viability of use within an operating plant. Information about each technology is provided for each metric when available. These metrics are discussed below.

Leak Detection Sensitivity

The foremost metric is the leak detection sensitivity of the technology. For this investigation, the target detection sensitivity is on the order of 10^-2 mbar*L/s, which is roughly 1 gallon/day under standard condenser operating conditions.

Ability to Provide Qualitative or Quantitative Estimation of Leak Magnitude

Some of the established inspection methods are capable of identifying the presence of a leak, but provide little or no information about the magnitude of the leak. Other technologies are either able to directly measure the leak rate or they can provide information about the dimensions of the leaking flaw.

Accuracy of Method and Susceptibility to Noise or Uncertainties

Factors that affect the inspection method’s capability to reliably detect a leak are described. These factors may include environmental conditions that affect the measurement method, limitations of the instrumentation that add noise to the reading, or procedural elements that add uncertainty to the results.

Dependency on Operator Skill and Repeatability

Some methods require extensive operator training in order to produce useable results, whereas other methods require very little training. Also, some methods are more subject to the interpretation of the operator than others. The level of interpretation inherent to a method can affect the repeatability of the results.

Amount of Time Required to Perform Inspection

Both the amount of time required to set up for an inspection and the amount of time required to perform the inspection and data analysis on each tube is considered.

Suitability of Inspection Method for Reporting

The type and quality of the data produced by each inspection method affects the presentation of the inspection report. Some of the inspection methods generate data records during the inspection procedure that directly lend themselves to reporting, whereas other methods require intermediate recording and reporting steps that introduce subjective interpretation of the information.

Presence of Procedural Restrictions or Complications

Some inspection methods are relatively non-intrusive and require little preparation to perform. Other procedures may require more complicated tasks, including more involved disassembly of plant components, EPA guidelines on the disposal of consumables, stringent code requirements imposed on method, and other factors.

In addition to these metrics, an attempt was made to include a metric to evaluate the cost of each inspection method. Efforts to evaluate the cost of multiple methods in a balanced fashion were not successful. The rates for each available inspection method vary from one inspection vendor to the next. Plant operators were reluctant to provide quantitative information about the cost of different inspection methods. Furthermore, when asked to evaluate the relative expense of one method versus another, vendors tended to respond with, “everything is expensive,” or “it costs too much.” Finally, a few of the inspection methods are relatively new and rarely employed, meaning there isn’t significant industry familiarity with the costs of the method. As a result, information about the expense of each method is excluded. It is possible that in the future, a more dedicated study related to evaluating the expenses related to each method could be evaluated. Such a study may be relevant to a cost benefit analysis of plant maintenance performance.

5

CONDENSER TUBE LEAK INSPECTION METHODS

Early approaches to condenser tube inspection made use of shaving cream, plastic wrap, and cigarette smoke applied to the tubesheets to find evidence of gross in-leakage in the tubes. These rudimentary techniques were very easy and inexpensive to apply, but were unreliable and may have carried undesirable side effects. In many cases, the early inspection methods provided no method of verifying the presence of leakage within suspect tubes, leading to many falsely identified leaks and some missed leaks.

When a leaking tube is identified, maintenance procedures call for the tube to be plugged, which effectively removes it from operation. Due in part to the low certainties of the early inspection methods, the power industry adopted a policy of insurance plugging, where tubes surrounding a tube with a suspected leak were also plugged. As a result, the condensers would experience diminished capacity and reduction of its effective life cycle.

As the power industry developed an improved understanding of plant maintenance and operating efficiency, guidelines were developed for condenser water in-leakage tolerance. Presently, most operating facilities operate with an effective zero leak tolerance. To meet this goal, the power industry has developed inspection practices that provide increasing detection sensitivity, reliability, and traceability. This section outlines the most common condenser tube inspection practices that are currently in use. The basic operating principle of each method is described along with a general description of the tube inspection procedure. Information about the performance of each technology based on the metrics listed in Section 4 is also provided.

It is worth noting that most of the inspection technologies share a few recurring conventions to access the condenser tubes for inspection. Depending on the access requirements of the technology, inspection must either be performed during a plant outage when the condenser is out of service, or inspection must be performed when the condenser is under some load. The most common access convention occurs when the condenser is under partial load and when one or more waterboxes have been isolated. Under these conditions, the remaining waterboxes can continue to carry cooling water into the tubes that remain enclosed, so the condenser is able to continue to maintain vacuum at a reduced efficiency. This mode of operation allows the inspector to examine the exposed tubes and to take advantage of the pressure differential across the tube walls. In the remainder of this section, this approach to inspection is referred to as the "partial load exposed tubesheet" approach. Other access approaches are described for each technology.

Chemical Reagent and Conductivity Measurement

Many power plants employ continuous water chemistry monitoring technologies within the condenser and throughout the plant. Although these technologies are not technically inspection technologies for leak detection, they usually provide the first indication that an identifiable or significant leak is present within the condenser. Depending on their type, these sensors can be found within the condensate vents at the top of the hotwells, within the non-condensable off-take lines, or in the condensate drain lines. They may also be present throughout other parts of the plant such as the further downstream from the condenser exhaust lines, within feedwater heaters, and within the steam generators. By continuously monitoring the water chemistry at multiple points within and around the condenser, it is possible to detect the formation of significant coolant water leaks (as well as air in-leakage). If multiple probes are present within the condenser, it is also sometimes possible to isolate the part of the condenser where coolant water in-leakage is present, which may permit inspectors to more rapidly isolate the leak during inspection.

The most common water chemistry monitors found within a plant include pH monitors, specific conductance sensors, cation conductivity sensors, specific ion electrodes, and particulate measurement sensors. pH monitors measure the hydrogen concentration in water to determine the concentration of cations. There are several accepted variations of the pH sensor. One common design is the glass pH electrode, which consists of a pH reference cell, a wet electrode, and a temperature compensation element. pH monitors are easy to use, but tend to provide only a coarse indication of leak rate. pH monitors tend to be susceptible to many factors. For example, the concentration of non-condensable gases also affects the value of pH. As a result, these sensors are only reliable for the detection of major leaks.

A specific conductance sensor uses one or more pairs of electrodes to directly measure the conductivity of the water flowing between the electrodes. The measurement may either be conducted through a derivation of Ohm’s law by measuring the current through the water for a given voltage drop across each electrode pair, or it may be conducted inductively by measuring the voltage potential induced for a pulsed current. Within the condenser, a tray dedicated to conductivity measurement may be located at the top of the hotwell below each tube bundle. Specific conductance sensors are able to measure the presence of contaminants to the order of 20 parts per billion within water.

A cation conductivity sensor passes the condensate of a water sample through an ion exchange resin to convert the cations into an acidic effluent. The conversion produces a much more conductive solution. After this conversion, conductivity is measured using the same process as the specific conductance sensor. Cation conductivity sensors can measure the presence of contanamints on the order of 1 part per billion within water.

A specific ion electrode uses an ion-selective membrane that is designed to respond to the presence of a specific ion in a solution. The membrane generates a voltage potential in response to an ion transport process when the selective ion is present in the solution, where the voltage level is proportional to the concentration of the specific ion. The most common type of specific ion electrodes used in power plants are designed for the detection of Sodium, although other specific ion electrodes have been included to detect Chloride, Sulfate, Silica, Calcium, and other cations. Typical on-line sodium monitors measure sodium content at contaniminants of less than 0.1 part per billion.

Particulate measurement sensors are a more recent development. They use the concept of nephelometry (light scattering due to the presence of a specific particle) to measure the particle concentration in a fluid. By measuring the amount of light scattered onto an intensity sensor, it is possible to make a very accurate measurements of the amount of a specific particle present in the fluid. With this sensor, it is possible to measure the presence of contaminants on the order of less than 1 part per billion within water.

Leak Detection Sensitivity

All of the described water chemistry monitors provide a means of directly measuring the amount of contaminants that are entering the water cycle instead of measuring the cooling water leak rate. Specific conductance sensors can measure concentrations to 20 ppb, cation conductivity sensors measure to 1 ppb, particulate measurement sensors can measure concentrations below 1 ppb, and specific ion electrodes can measure concentrations to 0.1 ppb. pH sensors are the least sensitive, and are generally only reliable for coarse evaluations of water purity change.

It is possible to estimate the total cooling water in-leakage into the steam water cycle for the sake of comparison to other inspection results, but some context about the cooling water is required. The content and concentration of contaminants in saltwater, brackish water, and fresh water varies significantly. For example, a salt water source will typically include approximately 3.5% salt by mass whereas a freshwater source will typically include less than 0.1% salt by mass. Therefore, a saltwater leak would introduce roughly 35 times the saline contaminant to the steam cycle as an equivalent freshwater leak.

As an example, a typical 500 MW turbine may require a cooling water mass flow rate in excess of 290 kg/s. For a condenser with 2 waterboxes, the water flow rate through each cooling water discharge line would be approximately 145 L/s. At a daily leak rate of 1 gallon (3.785 L), salt concentration sensitivity below 10 ppb would be necessary to detect a seawater leak, or less than 0.3 ppb for a freshwater leak.

Ability to Provide Qualitative or Quantitative Estimation of Leak Magnitude

All of the water chemistry measurement technologies provide an estimate of the concentration of one or more contaminants within the condensed water. Based on the known properties of the cooling water, it is possible to estimate the rate of contaminant ingress into the water-steam cycle using the measured concentration. These measurements will yield the aggregate leak rate into the condenser instead of the leak rate for a given flaw.

Accuracy of Method and Susceptibility to Noise or Uncertainties

Plant operators have found that the accuracy of these sensors is somewhat dependent on their placement in the condenser. They appear to perform most reliably when located either in the hotwell or within the condenser drain lines, where condensed water has become properly mixed and there is less sample contamination due to two-phase water and non-condensible gasses. In these parts of the condensers, the performance of the sensor appears to be reliable. The exception is the pH meter, which has a history of being susceptible to a wide range of factors (concentration of gasses, varied responses to different mixtures of different contaminants, etc.). As a result, while the pH meters may be useful for identifying the onset of a problem within the condenser, they have not been reliable at determining the nature or severity of the problem.

Dependency on Operator Skill and Repeatability

The majority of the water chemistry meters include readouts that can either be manually polled or that can be tied in to the plant data network and automatically queried. These sensors require little maintenance and are therefore not sensitive to operator skill. The specific ion electrodes are the possible exception. Due to their operating principle and their sensitivity, these sensors need to be carefully monitored and regularly recalibrated to ensure proper indications.

In plants with older water chemistry monitors, sample analysis is completed manually outside of the condenser. In this case, the effectiveness of the measurement is dependent on the technician's ability to remove the collected sample without contaminating it with exposure to atmosphere or other fluid mixtures from another part of the condenser, and on the technician's ability to perform the sample analysis.

Amount of Time Required to Perform Inspection

In the case of online sensors, there is a settling time on the order of minutes between each measurement, but all measurements are made during standard operation. Therefore, there is effectively no time commitment to acquire the sensor readings.

Suitability of Inspection Method for Reporting

In cases where the monitors are tied into the plant data network, the automatic polling of the monitors provides nearly continuous measurement of the contaminant concentration in the steam-water cycle. This logged information is very suitable for online tracking and reporting of potential leak events. Similarly, in the case of manual logging, although the data is less continuous, good logging practice can lead to reliable tracking and reporting of potential leak events.

Presence of Procedural Restrictions or Complications

Sufficient information could not be collected during the study to evaluate this metric.

Visual and Video Probe Inspection Methods

Visual inspection of the condenser as a whole is inherent to almost all condenser maintenance programs. Visual inspection is conducted on most of the major structural components, including the condenser shell, waterboxes, tubesheet, all joints and seals, but the tight configuration of the tube bundles limits the amount of visual inspection that can be conducted on the tubes themselves. Therefore, plant operators rely on only minimal visual inspection of the tubes to determine possible damage mechanisms.

The most common visual inspection of the tube outer diameters occurs in the form of a cursory check of the outermost tubes within the tube bundle from within the shell, and inspection of the tube-to-tubesheet joints and cooling water entrance regions within each tube. During plant outages, it is common for inspectors to enter the condenser shell to look for steam impingement, debris buildup, structural damage, or other common problems. At this time, the tubes are checked for obvious signs of wear or damage on the tube surfaces. In particular, inspectors will check to see if there is any interference between the tubes and the support plates that may lead to cracking. If a pattern of corrosion is observed over a specific area of the tube bundle, then the plant operators may take action to prevent further damage, but it is rare to identify leaking tubes using this approach.

During tube cleaning activities, the tubesheets are often evaluated for signs of corrosion and fouling. Particularly in cases where the tubesheets and the tubes are composed of similar materials, the condition of the tubesheet can serve as an indicator of the internal condition of the tubes. Inspectors will typically look for signs of general corrosion over the tubesheets and signs of turbulence-induced pitting corrosion at the tube openings. If heavy fouling is present, then the fouling may be sampled and characterized to determine whether a change to the chemical treatment of the cooling water is required.

Many condensers employ a cathodic protection system within the waterboxes. As part of this system, an arrangement of sacrificial anodes, or waste plates, is bolted to the inside of the waterboxes. The anode array is typically composed of a combination of Zinc, Magnesium, and Aluminum plates, but many anode arrays also include plates composed of the same material used to make the tubes. During inspection, the corrosion rates on these plates can be used to make order-of-magnitude estimates of the corrosion rates within the tubes.

Another common visual inspection technique involves using a borescope or videoprobe to determine the extent of fouling and scaling damage on the interior of the tubes. Modern videoprobes meant for tube inspection include software capabilities that allow for the measurement of fine features within the recorded video data, such as the depth and extent of a pit or the length of a feature protruding from the tube wall. To provide accurate measurements of recorded features, the dimension scale of the recorded image is calibrated against a feature of known size. Measured features are then scaled to actual size based on projection calculations and on its location within the camera's field of view. In addition to determining the degree of fouling that has developed within the tubes, this information is useful for determining the amount of cleaning that is required before inspection methods that require access to tube walls (such as eddy current) will become effective.

Leak Detection Sensitivity

The sensitivity of both visual inspection methods and videoprobe inspection to leaking flaws is qualitative at best. Visual detection will only find the most egregious leaks such as through-wall corrosion patches, dented tubes, open cracks, and signs of water weepage.

Ability to Provide Qualitative or Quantitative Estimation of Leak Magnitude

Because visual inspection will only detect larger flaws, the flaws can generally be physically measured, but the leak rate through these flaws can only be qualitatively estimated.

Accuracy of Method and Susceptibility to Noise or Uncertainties / Dependency on Operator Skill and Repeatability

Because visual inspection requires the detection of damage through eyesight, the technique is highly dependent on the quality of the working conditions, lighting, experience level of the inspector, and pace of or allotted time for the inspection. A defect is much more likely to be found if it is well illuminated, located in an easily accessible part of the condition, and if the inspector is conducting a thorough sweep of the tubes and has observed other real-world flaws. Furthermore, the overall cleanliness and condition of the tube can affect the success rate of visual inspection. In a fairly clean tube, defects are more apparent. In a heavily corroded tube with excessive fouling, leaking flaws are more likely to be masked.

Amount of Time Required to Perform Inspection

The amount of time spent conducting visual inspection can vary widely based on the inspection procedures called for by the plant operators.

Suitability of Inspection Method for Reporting

Visual inspection requires manual entry of all findings. Many plants provide inspectors with visual inspection forms that include tube maps, sketches of major components, and comment entry fields. It is common to find visual inspection reports in the form of scanned handwritten notes. In some cases, these reports may be accompanied by photographs of identified flaws. In the case of videoprobe inspection, images and video data of some tube inspections may be saved for later review, but this is rare.

Presence of Procedural Restrictions or Complications

Sufficient information could not be collected during the study to evaluate this metric.

Vacuum Pressure and Overpressure Methods

Several techniques have been developed that rely on a pressure difference between the cooling side and steam side of the condenser to produce an observable indication of leakage. These methods are described as either vacuum pressure and overpressure test methods. The most common of these methods include:

- tube drip testing (overpressure of cooling side),
- soap or foam testing (vacuum pressure of steam side),
- hydrostatic fill testing (overpressure of steam side),
- tube pressure decay testing (overpressure of cooling side), and
- dimple plug testing (vacuum pressure of steam side).

Tube Drip Test

The most primitive method still in use today is the tube drip test. In this test, the water boxes are filled with cooling water at a low positive pressure. Inspectors then enter the condenser shell and visually inspect each visible tube for signs of leaking water. In some cases, an oil or solvent is added to the cooling water. The oil reduces the fluid viscosity, which improves the chance of detecting a leak. Another approach is to heat the water within the waterbox, which will also reduce the fluid viscosity. If a tube with a clear indication of a leak is identified, then it is plugged.

Leak Detection Sensitivity

Leaks on the order of 10^-2 mbar*L/s are detectable on individual tubes using this method, provided the surface of the tube can be seen from within the condenser shell. It is possible to detect smaller leaks (as small as 5x10^-4 mbar*L/s), but the detection of smaller leaks requires special procedures and longer waiting periods to report leak rate. As a result, if multiple leaks are present within a tube bundle, then the leak water has more time to collect and pool far from the leak, resulting in greater difficulty in isolating the leak source.

Ability to Provide Qualitative or Quantitative Estimation of Leak Magnitude

This method is extremely qualitative. The presence of a leak can be detected, but due to the transport of water over the tube surface, it is difficult to quantify the leak volume from any given leak source.

Accuracy of Method and Susceptibility to Noise or Uncertainties

Because this test method depends on water accumulation on the outside surface of the condenser tubes, it is dependent on the cleanliness and dryness of the tube prior to the start of the test. It can also be dependent on the moisture content and temperature of the surrounding environment.

Dependency on Operator Skill and Repeatability

This method is analogous to visual inspection methods in that the inspector must observe the leak in order to detect the flaw. The test is highly operator dependent based on the operator's effectiveness of locating dripping water.

Amount of Time Required to Perform Inspection

At standard detection limits on the order of 10^-2 mbar*L/s, a leaking tube will show signs of water weepage within 30 seconds of pressurization. By necessity, inspectors are challenged to identify leaking tubes quickly before leaking water is allowed to run and pool in other locations. In many cases, inspectors are not able to identify individual leaking tubes before the leak source is obscured by water runoff. The total inspection time depends on the procedures adopted by the plant.

Suitability of Inspection Method for Reporting

All leak indications must be manually identified and recorded by inspectors. The inspection procedure must specify the documentation practices and forms to be used during inspection. The inspection report must be generated from these forms after inspection.

Presence of Procedural Restrictions or Complications

Sufficient information could not be collected during the study to evaluate this metric.

Soap or Foam Test

An alternative method to the tube drip test is soap testing, which can be performed while the plant is online. In a soap test, one pair of the water boxes is removed from the condenser. On one side by entering the waterbox, the exposed tubes are plugged, and on the opposite side, the exposed tube sheet is covered in a soap or foam spray. Historically, one of the most popular foam sprays for this test has been shaving cream. If a leak is present in a tube, the foam is drawn into the tube opening, leaving an exposed opening in the foam coating on the tube sheet. The soap or foam must be cleaned from the tubesheet and the tubes after completion of the test.

Leak Detection Sensitivity

The foam coating on the tubesheet must have sufficient surface tension to remain undisturbed in areas where there are no leaks, but low enough surface tension for the foam to be drawn into tubes with leaks. Effective tests have shown that using appropriate foam sprays, leaks on the order of 10^-2 mbar*L/s can be detected.

Ability to Provide Qualitative or Quantitative Estimation of Leak Magnitude

This method is qualitative.

Accuracy of Method and Susceptibility to Noise or Uncertainties

The success of this method relies on the ability to lay a clean coating of foam over the tubesheet and protect that coating from perturbation until the test procedure is completed. Use of a weak foam spray or poor application of the foam spray can lead to falsely identified tubes.

Dependency on Operator Skill and Repeatability

The method is limited to the inspector's ability to identify foam ingress into the tubes and the inspector's ability to spread a clean and consistent foam coating over the tubesheet.

Amount of Time Required to Perform Inspection

In early tests, large areas of the tubesheet would be coated with foam and then the coating would be studied for gaps after several minutes. Inspectors have determined that there is a lower risk of false calls if smaller areas of the tubesheet are inspected at one time. For a given area of the tubesheet measuring a few square feet, a foam layer can be applied and allowed to be drawn into leaking tubes over a period of 4 to 5 minutes. The inspection rate will depend on the foam coverage area for any given test.

Suitability of Inspection Method for Reporting

All leak indications must be manually recorded by inspectors. The inspection procedure must specify the documentation practices and forms to be used during inspection. The inspection report must be generated from these forms after inspection.

Presence of Procedural Restrictions or Complications

Many plant operators require all foam to be cleaned from the tubesheet after testing and that all foam is purged from the tubes. Some foam sprays contain chemicals that can act as contaminants if allowed to enter the plant water-steam cycle.

Hydrostatic Fill Test

In some cases, it is possible to perform a hydrostatic fill test on the condenser. In this test while the unit is off-line, the condenser shell is sealed off from the remainder of the water cycle. Prior to performing this test, the tubesheets and the interiors of all tubes must be carefully cleaned and dried. Then, the shell volume is gradually filled with demineralized water at a rate of roughly 1-2 cm per minute. As the water level rises in the condenser shell, inspectors visually check for weeping tubes as successive rows of tubes within the tube bundle become submerged. Once the water level reaches a height of roughly 1 meter above the top of the tube bundles, the water is allowed to stand for approximately 12 hours, and then the tube sheets are rechecked for any additional weeping tubes. All tubes with indications of leakage are plugged.

Leak Detection Sensitivity

This method is effective at detecting leaks on the order of 5x10^-3 mbar*L/s.

Ability to Provide Qualitative or Quantitative Estimation of Leak Magnitude

This method is qualitative.

Accuracy of Method and Susceptibility to Noise or Uncertainties

To detect small leaks, the tube interiors must be very clean, and both the tubes and tubesheet must be dry. The method relies on water leaking into the tube and weeping out of the tube ends. If there is significant fouling or scaling within the tube, then the leaking water may not reach the tube end and the leak will not be detected.

Dependency on Operator Skill and Repeatability

This method requires fairly little skill to perform. The success of the procedure is essentially dependent on the ability of the operator to identify water leaking from individual tubes. When and where permitted, a dye may be added to the water used to fill the shell side of the condenser. The florescence in the dye permits the use of an ultraviolet light to facilitate the identification of the leaking tube(s).

Amount of Time Required to Perform Inspection

The inspection time is entirely dependent on the fill rate and standing time for the water as specified by the inspection procedure. The standard fill rate is 1-2 cm/minute, and the standard standing time is 12 hours. At this rate, a large condenser can be screened within about 1.5 days. Some hydrostatic fill test procedures specify that if a certain number of leaking tubes are discovered, then either another hydrostatic test or other testing procedures must be performed after repairs are made to the condenser.

Suitability of Inspection Method for Reporting

All leak indications must be manually recorded by inspectors. The inspection procedure must specify the documentation practices and forms to be used during inspection. The inspection report must be generated from these forms after inspection.

Presence of Procedural Restrictions or Complications

The Environmental Protection Agency and other regulatory bodies are considering requirements for water to be tested and/or treated after use for hydrostatic testing of certain types of vessels, including power plant condensers. If this becomes a requirement, then the test will require additional steps for removing and treating the test water.

Pressure Decay Test

In pressure decay testing, each end of a tube with a suspected leak is plugged and pressurized with air, and the tube internal pressure is monitored for a period of several minutes. If the internal pressure drops significantly signifying a leak, then the tube is plugged. Due to the amount of time required to perform this test, pressure decay testing is not an efficient test method for an entire tube bundle. The test is also subject the quality of seal that can be made on either end of the tube during the test.

Leak Detection Sensitivity

The measurement sensitivity of this technique is directly dependent on the amount of time the inspector is willing to spend testing each tube. It is also dependent on the resolution of pressure measurement, the tube dimensions, and the peak starting pressure applied to each tube. Under standard conditions, pressure decay tests are designed to detect leaks on the order of 10^-2 mbar*L/s. With sufficient time and appropriate testing equipment, leaks on the order of 10^-4 mbar*L/s can be detected.

Ability to Provide Qualitative or Quantitative Estimation of Leak Magnitude

This test can be performed quantitatively. If the rate of pressure decay is measured inside the tube and the pressure within the condenser shell is known, then the gas leak rate can be calculated. Using the gas leak rate, it is possible to calculate the leak rate for water.

Accuracy of Method and Susceptibility to Noise or Uncertainties

The accuracy of the test method is dependent on the temperature stability of the tubes during testing and the purity of the test gas used to pressurize the tubes. The gas leak rate will depend on how well these factors are known. The accuracy of the pressure decay equipment will also affect the measurement resolution of the leak. At the lower limit of the leak detection range, the quality of the seals on either side of the tube during testing may also become a factor in the quality of the results.

Dependency on Operator Skill and Repeatability

With the appropriate equipment, this test can be performed almost automatically. The test repeatability is very good and the possibility of operator error is minimal.

Amount of Time Required to Perform Inspection

The amount of time required to perform this test is dependent on the leak rate that must be detected. Under standard conditions, each tube can be tested within 2 minutes. At this rate, testing each tube in the condenser would be prohibitive, requiring weeks.

Suitability of Inspection Method for Reporting

Sufficient information could not be collected during the study to evaluate this metric.

Presence of Procedural Restrictions or Complications

There are no known procedural restrictions.

Dimple Plug Test

In the past decade, dimple plug testing has become a popular online testing method. This test is performed using the partial load exposed tubesheet approach. All of the exposed tubes are plugged on either end with a specialized rubber plug. If a leak is present in one of the tubes, then the vacuum pressure will eventually draw most of the air out of the tube. The rubber plugs include a diaphragm or membrane on the exposed end. If there is a leak present in one of the tubes, then suction created within the tube will draw the membrane into the plug, leaving a visible depression on the rubber stopper. Once installed, the plugs are left in place for a period of 12 hours, and then all tubes that include a depressed membrane are marked as leaking.

Leak Detection Sensitivity

The entire volume of the plugged tube must be evacuated to some low pressure for the dimple plug to react. As a result, the leak detection sensitivity is on the order of 10^-2 mbar*L/s.

Ability to Provide Qualitative or Quantitative Estimation of Leak Magnitude

This method is qualitative.

Accuracy of Method and Susceptibility to Noise or Uncertainties

This method is fairly straight-forward. The most significant cause for error is poor sealing between the tubes and the plug, which can result in missed leaks.

Dependency on Operator Skill and Repeatability

This method requires minimal skill to conduct.

Amount of Time Required to Perform Inspection

For this method, dimple plugs must be installed on each end of several thousand tubes and then checked for sealing. This installation process can take several hours. After installation, the recommended wait time before inspection is 12 hours. Again, inspection and subsequent removal of the dimple plugs will require several more hours.

Suitability of Inspection Method for Reporting

All leak indications must be manually recorded by inspectors. The inspection procedure must specify the documentation practices and forms to be used during inspection. The inspection report must be generated from these forms after inspection.

Presence of Procedural Restrictions or Complications

There are no known procedural restrictions.

Thermal Conductivity and Infrared Inspection Methods

Traditional thermographic techniques have been demonstrated as an effective means to rapidly screen the condenser shell (and other structures) for air in-leakage or for leakage of hot fluids. In thermography, an infrared camera is used to look for anomalies in the temperature profile of a structure. In most cases, a large structure will have a fairly predictable temperature profile over a large area. This profile may either be relatively invariant across the structure’s surface, or it may have a gradient from one location to the next. For example, on the condenser shell, it is typical for the shell surface temperature to be notably elevated above ambient temperature, but to have a temperature gradient from the expansion joint to the hotwell. If a leak is present in the shell, then ambient air is sucked through the shell into a vacuum, causing the air to rapidly expand. This produces a highly localized cooling effect immediately around the leak that appears as a discontinuity in a thermal image. By looking for these discontinuities in otherwise predictable temperature profiles, it is possible to rapidly screen for leaks.

Based on the success of detecting air in-leakage on the condenser shells, attempts were made to detect leaks in the tubes close to the tubesheet by measuring the temperature gradient on the tubesheet itself. In these attempted studies, the waterbox was removed from the tubesheet on either end and the condenser was operated under partial load. It was believed that if a leak was present near to the tubesheet, then air would be drawn through the tube and out the leak, which would produce a temperature gradient in the tube that might affect the tubesheet. Initial tests indicated that this approach would not be successful. Generally, it was found that the thermal gradient across the tubesheet was much less consistent than on other structures, and that the effect of a leak within the tube was extremely minute. As a result, the approach led to a high degree of uncertainty in the inspection and a high incidence of false calls and missed calls. Further investigation of this approach has not been pursued.

An older alternative inspection method involved using a thermal conductivity leak detector. With this tool, the premise was to flood the tube with a high concentration of a gas with a different thermal conductivity than air (Helium, Carbon Dioxide, Argon, etc.). The thermal conductivity probe was passed over the outside of the tube, which drew present gasses into a chamber that would measure the heat rate through the gas. This heat rate was compared against a second reference chamber that would measure the heat rate through ambient air. If a sudden change in heat rate is detected in the gasses sampled by the probe, then a leak is suspected.

Although conductivity leak detectors are used for other applications, the testing method never gained popularity in condenser inspection due to inherent complications related to tube access. Unlike other methods, this method requires that the test gas evacuate into another ambient gas, which meant that two known gasses must be present on either side of the leak barrier. Because the probe must be passed over the outside of the tube, it required testing within the condenser shell. If more than one leak was present within the condenser, then buildup of the test gas within the shell would occur, which would ultimately contaminate the ambient air that was used for reference sampling. Due to these complications, the thermal conductivity leak detection method was not adopted for condenser inspection. Work on this method did ultimately lead to a more recent technological development, the tracer gas inspection method.

Acoustic Leak Detection

Acoustic leak detection relies on the measurement of sound waves to detect the presence of a leak within the structure. Acoustic leak detectors are normally handheld ultrasonic devices that operate in the frequency range of 20 kHz to 200 kHz. These frequencies are above human audible range, but are low enough for effective sound propagation through air and most other gases. An acoustic leak detector generally consists of one or more ultrasonic detectors (either a transducer or a microphone), a sound focusing nozzle, a sound sensitivity meter, and some sampling and recording electronics. Most detectors also include a headphone connection and a heterodyne circuit that is used to downshift the signal into the human audible range. By downshifting the signal, it is possible for the inspector to hear the presence of a leak during the testing procedure.

Vacuum and Pressure Acoustic Leak Detection

There are two commercially employed acoustic leak detection methods: vacuum leak detection and pressure leak detection. The vacuum leak detection method is used when a difference in pressures is present across tube wall. If a pressure difference is not present during testing, then the pressure leak detection method can be employed, where each tube is filled with a static fluid under pressure. Under both methods, as fluid flows through the leak, it enters the leak orifice in a turbulent flow regime. The turbulent fluid produces a high frequency vibration that is ultrasonically detectable.

The vacuum leak detection method may be employed when the partial load exposed tubesheet access approach is possible. In the initial stage of testing, the inspector may record the sound level over large areas of the tube sheet in an attempt to localize regions of the tube sheet that contain damaged tubes. To support this task, a parabolic dish is affixed to the detector. Generally, this initial sweep of the tube sheet is only sufficient for localizing tubes with gross damage. Next, the detector is fitted with a focusing nozzle that can be used to isolate individual tubes, and each tube is individually interrogated. Leaking tubes are identified when a high frequency signal with spectral characteristics of a leak are detected. In some cases, the magnitude of the leak can be correlated to the amplitude of the leak signal, although factors such as proximity of leak to tube sheet make this measurement subjective.

If the condenser is a single pass system, then testing must be conducted during plant shutdown, and the pressure leak detection method must be used. In this case, the water boxes are removed from the condenser to access the tube sheet on both sides. One tube is plugged from both sides and pressurized with air. The leak detector is fed through a manway on the condenser shell to a location near the plugged tube. If a leak is present within the plugged tube, then the distinctive ultrasonic leaking signal should be recorded by the detector.

Calibration of the detection system is required for both the vacuum leak method and the pressure leak method. For successful testing, some knowledge of the background noise level and the characteristic signals of the condenser are required. Ideally, the inspector will have access to information on what an undamaged tube sounds like before testing. In some cases, the inspector will also calibrate the detector on a test sample with a known leak and under controlled fluid and pressure conditions prior to testing the condenser.

Leak Detection Sensitivity

The absolute detection limit of an acoustic device is dictated by the lowest level signal that the device can measure. Modern acoustic detectors can measure sound levels as low as -10 dB_{SPL}. Anecdotally, this is equivalent to the signal level output of a leak rate on the order of 5x10^-3 mbar*L/s. In actual field conditions, the true detection limit is highly subject to the acoustic noise levels of the testing environment. In practical working conditions, the smallest detectable leaks are typically on the order of 10^-2 mbar*L/s using vacuum leak and pressure leak detection methods.

Ability to Provide Qualitative or Quantitative Estimation of Leak Magnitude

Acoustic detection methods are largely qualitative. Some effort is made to estimate leak magnitude by conducting calibration tests on standard samples and measuring the signal response, but amplitude response can be significantly affected by the shape of the leak, the distance between the leak and the microphone, and the environmental conditions such as temperature and humidity

Accuracy of Method and Susceptibility to Noise or Uncertainties

Acoustic methods are highly susceptible to the acoustic noise conditions within the test area. The background acoustic noise often acts as the limiting factor for the smallest leak that can be detected. Many acoustic testing procedures call for testing on calibration flaws to establish the frequency response of different types of flaws. With this information, the detected acoustic signals can be filtered for signals within that frequency range. In an environment such as a plant floor, the rotating machinery, pumps, gas and water lines, and electrical equipment all produces low level signals in the same frequency range. Apparently, even florescent lights can be a troublesome noise source because they generate sound in the frequency range of common target leaks.

Dependency on Operator Skill and Repeatability

The success of acoustic methods are highly dependent on operators with a background of experience in listening for and identifying leak signals for a large number of other acoustic sources. An inspector must receive prior training and field experience before they are equipped to detect leaks.

Amount of Time Required to Perform Inspection

Sufficient information could not be collected during the study to evaluate this metric.

Suitability of Inspection Method for Reporting

In the majority of cases, inspector will rely on written inspection forms based on plant inspection procedures to report any detected leak indications.

Presence of Procedural Restrictions or Complications

There are no known procedural restrictions.

Acoustic Tone Detection

A third method called the acoustic tone method exists, but the method appears to be in the experimental stages of field testing. The acoustic tone method must be performed when the condenser is offline. One inspector enters the condenser shell and blasts the tubesheets with carefully tuned bursts of acoustic noise. At the tubesheet, another inspector listens for the acoustic tones with an acoustic leak detector using the same approach used in the vacuum leak detection method. The acoustic response of each tube is recorded by the acoustic leak detector, and signal processing techniques are used to compare the recorded acoustic signal to the transmitted tones. Theoretically, if an open flaw is present within the tube, then the amplitude response of the recorded tone will be greater (louder) than the response from the surrounding tubes. Because the sound characteristics of the transmitted signal are known, the signal processing techniques largely eliminate the effect of the background noise level, permitting the detection of lower leak rates.

Internal Rotary Inspection System (IRIS)

Ultrasonic Internal Rotary Inspection System (IRIS) is a wall thickness measurement technique. The IRIS probe consists of a single element ultrasonic transducer, a rotating ultrasonic mirror, and a centering sled. An illustration of the probe is shown in Figure 5-1.

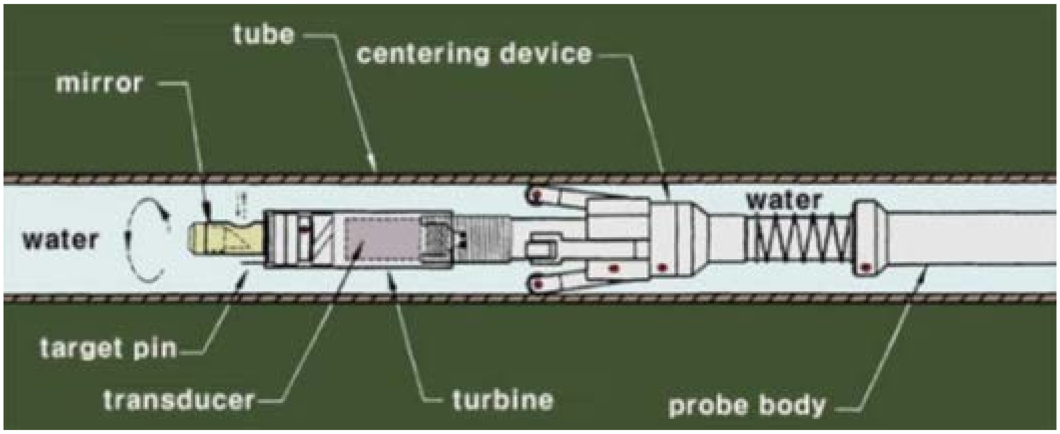

Figure 5-1
Illustration of an IRIS Probe

IRIS inspection of the tubes must be conducted after tube cleaning activities. After the tubes have been cleaned, each tube is flooded with water, and the IRIS probe is pushed through the tube. As the centering sled is pushed through the tube, the ultrasonic transducer directs a wave along the tube's central axis. The wave impinges on the mirror and reflects radially outward through the tube wall. As the wave encounters the inner diameter and outer diameter of the tube, signal reflections return to the ultrasonic transducer and are recorded. For a known ultrasonic wave speed in the tube material, the tube wall thickness at each measurement location can be calculated from the time difference between the inner and outer wall reflections. As the IRIS probe is drawn down the length of the tube, the mirror spins at high speed, redirecting the wave around the full circumference of the tube. The combination of the forward motion of the probe assembly and the rotation of the mirror produces a helical data collection pattern. By controlling both the mirror spin rate and the sled speed, it is possible to map the wall thickness of the entire tube.

Leak Detection Sensitivity

The IRIS technology is much more suited to detecting ID and OD corrosion patches than small cracks or pinhole leaks. In terms of wall thickness, the technology is capable of measuring thickness changes as small as 0.1 mm, but a through-wall hole may need to be more than 1 mm in diameter before it becomes apparent in the IRIS inspection data. An opening of that size in a tube would produce leaks with volume flow rates approaching 1.5 L/s. Therefore, the IRIS technology is very effective at characterizing general corrosion, pitting corrosion, small dents and gouges, and larger open cracks, but it is not useful for detecting small hairline cracks or pinholes that would produce smaller leaks.

Ability to Provide Qualitative or Quantitative Estimation of Leak Magnitude

Provided the leaking flaw is large enough to be detected, the IRIS technology will provide accurate measurements of the flaw dimensions. If the flaw dimensions are known, then the leak magnitude can be reasonably estimated.

Accuracy of Method and Susceptibility to Noise or Uncertainties

The tube inner surface must be very clean for this inspection method to work. Any accumulation of fouling or scaling on the inner surface will prevent the tool from making a wall thickness measurement in the affected area. Furthermore, if the tube is heavily dented or out of round, the probe can lose its centering within the tube, which will negatively affect the measured signal quality and the accuracy of the measurement. Assuming the tube is clean and fairly round, the technology is able to produce very accurate measurements of the tube wall thickness.

Dependency on Operator Skill and Repeatability

Inspection using the IRIS method requires calibration on similar or identical tubes with known flaws prior to conducting the inspections. Inspectors must be trained in basic ultrasonic testing principles and have familiarity with automated ultrasonic testing techniques to perform this inspection. Provided the calibrations are performed, the inspection method should be highly repeatable.

Amount of Time Required to Perform Inspection

The recommended scanning speed for an IRIS tool for 100% inspection of the tube interior is around 0.05 m/s, so inspection of a single tube may require several minutes of active scanning. Prior to scanning each tube, the tube must also be flooded with water to serve as an ultrasonic couplant. Between scanning time and setup activities between each tube, the IRIS technology usually cannot examine more than about 10 tubes per hour.

Suitability of Inspection Method for Reporting

The IRIS technology provides a digital record of each examined tube. The record provides a thickness map of the entire tube that provides information about the size and location of detected flaws as well as information about the remaining wall thickness of the entire tube. Many IRIS tools also provide tubesheet mapping software to help inspectors to identify the condition of each tube in the tubesheet.

Presence of Procedural Restrictions or Complications

There are no known procedural restrictions.

Guided Wave Inspection

Ultrasonic Guided Wave Testing

Ultrasonic guided wave testing technologies generally operate by generating a low frequency (60 – 250 kHz) ultrasonic wave that propagates down the length of the tube within the tube wall. For condenser tube inspection, the guided wave probe is inserted a short distance into the tube, and then the probe head is expanded to mechanically couple with the inner surface of the tube wall. The probe generates an ultrasonic pulse that travels as a guided wave down the length of the tube. If the traveling wave encounters a discontinuity within the wall, such as a corrosion pit, a crack, or a hole, then some of the wave energy is reflected back to the probe. Examples of two guided wave probes are shown in Figure 5-2.

Figure 5-2
Two Ultrasonic Guided Wave Probes for Tube Inspection

The magnitude of a signal response recorded by the guided wave probe is directly proportional to the cross-section of the tube that the signal's source interrupts. For example, if a 1 mm diameter through-wall hole is present within a tube with an outer diameter of 20 mm and a wall thickness of 1 mm, then the hole represents a total wall loss of approximately 1.7%, and the reflected signal amplitude for that hole will be nominally 1.7% of the transmitted signal.

The near end of the tube will typically reflect nearly 100% of the energy transmitted by the probe, so this signal is used as a reference for any signals detected within the tube. For every other signal, the approximate location of the signal source (flaw) can be determined by time-of-flight calculation, and the approximate magnitude is estimated by comparing the reflected signal to the reflected signal of the tube near end. The resulting ratio can be interpreted as the rough material loss in percent at the calculated location.

Leak Detection Sensitivity

Under good testing conditions, ultrasonic guided wave testing techniques are able to detect flaws as small as 1% of the tube cross-section. In the case of a standard 19 mm OD 18 BWG tube, this equates to the equivalent of a 0.55 mm diameter through-wall hole. A hole this size will have a leak flow rate on the order of 10 L/min.

It is also worth noting that ultrasonic guided wave testing techniques have acute sensitivity to closed cracks that are largely undetectable by most of the other leak detection systems. In many cases, these cracks can be detected before they penetrate the entire thickness of the tube.

Ability to Provide Qualitative or Quantitative Estimation of Leak Magnitude

Ultrasonic guided wave techniques are generally considered a "screening" technique. The testing method can provide information about the location and rough magnitude of the flaw, but it cannot provide exact dimensions of the flaw. In particular, the testing method is not effective at differentiating narrow, deep flaws from broad, shallow flaws. Therefore, the indication of a flaw does not necessarily equate to the presence of a leak within the tube.

Accuracy of Method and Susceptibility to Noise or Uncertainties

The effectiveness of the testing technique is often limited by the cleanliness of the tube. Tubes with high levels of fouling or scaling are very ultrasonically attenuative, and, therefore, may not be fully inspected. Furthermore, tubes with a high level of general corrosion may mask the presence of more serious flaws.

Dependency on Operator Skill and Repeatability

Ultrasonic guided wave inspection has historically required the use of highly trained technicians with extensive background in guided wave theory. During data acquisition, the inspector must be able to quickly evaluate the quality of data captured from each inspected tube to ensure that the probe is properly responding and that there is good coupling between the probe and the tube. Data interpretation is also more complex than in other inspection methods and requires more judgment to differentiate between geometry signals, defects, and extraneous ultrasonic guided wave modes.

Amount of Time Required to Perform Inspection

Because guided wave tube inspection can be conducted with one single-operator tool and the inspector need only access the tube sheets on either end of the condenser, tube inspection can be conducted rapidly. On average, 2 to 3 tube can be inspected per minute.

Suitability of Inspection Method for Reporting

The data analysis for the ultrasonic guided wave inspection method is more involved than the data analysis of other methods. For each tube, the collected waveforms must be evaluated for attenuation, geometry indication, multiple reflections, and extraneous wave modes before defect features can be identified. Once the defect signals have been separated from other waveform characteristics, they are characterized. The results of each tube inspection must be compiled into a report for the entire tube map.

Presence of Procedural Restrictions or Complications

There are no known procedural restrictions.

Acoustic Pulse Reflectometry

An alternative approach to guided wave testing involves using acoustic pulse reflectometry (APR) to generate a guided wave in the sonic frequency range that is air-coupled to the inner diameter of the tube. To use this method, the tube must be evacuated of all liquids.

A loudspeaker with a frequency range from around 10 Hz to 8000 Hz is coupled to the tube opening at the tube sheet, and a series of pulses are introduced into the tube. An example of an APR probe is shown in Figure 5-3.

Figure 5-3
APR Probe

As with ultrasonic guided waves, any change in the cross-section of the guided wave medium causes a reflection that is detected by the APR probe. Changes in cross-section can be caused by dents in the tube, deposits within the tube interior, and material wall loss within the tube interior.

Generally, data processing techniques are employed to determine the differences in the response of these three possible signal sources. One consequence of using the air volume within the tube as the wave transport medium is that APR cannot detect developing flaws on the outside diameter of the tube. Conversely, APR can be much more sensitive to an open pin-hole than ultrasonic guided wave techniques. This is due to the fact that an open pin-hole mechanically couples the air volume within the tube to the air volume surrounding the tube, which causes an amplified acoustic response to the flaw.

Leak Detection Sensitivity

Because APR relies on a propagating acoustic wave that is air-coupled to the tube interior, a through-wall defect produces a particularly strong signal compared to other defect signals. APR has been demonstrated to detect through-wall pin holes with diameters as small as 0.3 mm. A hole this size will have a leak flow rate on the order of less than 1 L/min.

Ability to Provide Qualitative or Quantitative Estimation of Leak Magnitude

APR is able to provide slightly better sizing information than traditional ultrasonic guided wave methods, but APR is still essentially a defect “screening” technique. It can provide some information about the apparent magnitude and location of a flaw, but it cannot provide information about actual dimensions.

Accuracy of Method and Susceptibility to Noise or Uncertainties

Because APR relies on the propagation of a sound wave in the acoustic range, high noise levels in an industrial environment may reduce the effectiveness of the technique. To overcome this, available APR systems have incorporated high levels of signal processing into the inspection technique to reduce the effect of ambient noise.

Dependency on Operator Skill and Repeatability

Compared to most technologies, APR requires only a moderate amount of training and field experience in order to become proficient in leak detection. Due to the signal processing requirements of APR, many systems handle a reasonable part of data analysis in the system internal signal processing, resulting in relatively recorded signals that are relatively intuitive to interpret.

Amount of Time Required to Perform Inspection

The inspection requirements for the APR technology are very similar to those of traditional guided wave inspection techniques. On average, two tubes can be inspected per minute.

Suitability of Inspection Method for Reporting

The acoustic response of each tube tested with APR is electronically recorded as a waveform, which can be stored and associated to the appropriate tube in the tubesheet map. After testing, each waveform can be analyzed and annotated, and the analysis results can be exported to an electronic record.

Presence of Procedural Restrictions or Complications

There are no known procedural restrictions.

Photoacoustic Gas Detection Method

Photoacoustic gas detection is a highly experimental detection method that relies on the measurement of sound waves to detect the presence of a leak. For this method, the interior of the tube must be flooded with a small amount of photoactive tracer gas such as sulfur hexafluoride (SF_6), and the detector must be located within the condenser shell. The outside of the flooded tube is irradiated with a pulsed laser, where the wavelength of the laser is tuned to the absorption frequency of the tracer gas. If a leak is present within the tube, then a gas plume will escape from the tube. As the laser illuminates the tube, the irradiated plume will rapidly expand and produce an acoustic pulse. The resulting acoustic wavefront can then be detected by a microphone. In particularly sophisticated systems, the inspector may use an array of microphones (such as a 3-by-3 grid) to not only detect the leak but pinpoint the leak location on the tube.

At this stage, the photoacoustic gas detection method is still very experimental and has seen only minimal field deployment for testing purposes. Tests so far have shown excellent leak detection sensitivity (on the order of 5x10^-5 mbar*L/s), but the test procedure is very involved, time consuming, and requires a significant amount of equipment. Furthermore, the test is only effective on tube surfaces that can be irradiated by the laser and that provide an unobstructed acoustic path to the microphone. Also, the use of a high power laser within the condenser poses a potential safety risk to inspectors. The testing method requires further development before it can be commercially applied to leak detection.

Eddy Current Inspection

Traditional Eddy Current Inspection

Eddy current inspection is one of the most widely accepted condenser tube inspection techniques currently in use. The testing method is useful for detecting corrosion, cracking, and pitting, and can provide information about the flaw size and location within the tube wall. To conduct eddy current, a bobbin probe with one or more wound electronic coils is rapidly pushed through each tube. As it moves through the tube, an alternating magnetic field is induced by the coils. These fields create eddy currents in the tube, which in turn generate a secondary magnetic field that opposes the magnetic field of the coil, thus changing the coil impedance. When eddy currents within the tube wall encounter a flaw, their normal flow is disrupted, which registers as a perturbation in the probe impedance. The phase and magnitude of the impedance response provides information about the type and magnitude of the flaw detected within the tube.

There are three basic eddy current probe types.

- Absolute – absolute probes generally have a single test coil that is used to generate the eddy currents and sense field changes. Absolute coils can be used for general flaw detection however they are very sensitive to changes in conductivity, permeability, liftoff, and temperature therefore steps must be taken to minimize these variables.
- Differential – differential probes have two active coils usually wound in opposition. When one of the two coils is over an area with a flaw and the other is over flaw-free material, a differential signal is developed between the coils. Differential probes are very sensitive to defects but are insensitive to gradually changing features such as wall thinning. Also, if a flaw is longer than the spacing between the two coils, only the leading and trailing edges will be detected due to signal cancellation when both coils sense the flaw equally.
- Driver-Pickup – Similar in design to a differential probe a reflection probe uses two coils. However, one is used to excite the eddy currents and the other is used to sense changes in the test material. The advantage of a driver/pickup probe is that each coil can be tailored to maximize its effectiveness. That is, the driver coil can be designed to produce a strong, uniform flux field in the vicinity of the pickup coil and the pickup coil can be made very small to increase sensitivity to small defects.

The three probe types are each suited to detecting a specific category of defects. Small defects such as pitting and cracking can be detected in the differential mode. Wall-thinning defects such as steam erosion or inlet end erosion are detected in the absolute mode. Driver-pickup coils can be used when the inspector is targeting a specific complex flaw type that is otherwise difficult to detect.

In addition to probe selection, modern eddy current equipment can drive the probe with up to 8 different interrogation frequencies. By driving the probe at more than one frequency, the inspector can gather better information about the flaw type and location in the wall (inner diameter or outer diameter), and is able to better differentiate between flaws, tube support structure (such as the tube support plates), and dents within the tube. For example, eddy current fields are subject to the skin depth effect, where the field strength decays at greater depths in to the material. In general, at very high interrogation frequencies, the field intensity is concentrated at the inner surface of the material, but decays rapidly through the material depth. At very low frequencies the field intensity can be fairly uniform through the material thickness.

One advantage of eddy current testing is that the test can be performed without any form of coupling medium between the probe and the tube wall, so the effectiveness of the test is not dependent on any water or gas. The technology is suitable for most metallic condenser tubes, but it is not suitable for ferrous metals such as carbon steel or for non-metallic materials. Furthermore, it is subject to high noise levels in certain large metals with coarse microstructure, such as certain types of cast stainless steels.

Prior to conducting a test, calibration of the eddy current probes and of the chosen test procedure must be conducted on test standards that have the same material properties and dimensions as the condenser tubes must be conducted. In many cases, calibration tubes with known flaw types are stored on-site at the plant for use by multiple eddy current vendors. Ideally, before conducting inspection, eddy current vendors will have access to benchmark eddy current data that was collected on the condenser tubes prior to initial operation. Based on initial available data and calibration efforts, an eddy current test plan will be devised that includes the appropriate interrogation frequencies, probe types, and probe travel speeds that are best suited to detecting the anticipated flaw types.

Leak Detection Sensitivity

With current eddy current bobbin probes, surface flaws with a length of 1-2 mm are detectable.

Ability to Provide Qualitative or Quantitative Estimation of Leak Magnitude

Provided the flaw is large enough to be detected by eddy current, the testing method is quantitative. Information about the flaw size, location along the tube, position within the tube wall, and sometimes even the flaw orientation can be derived from the test data.

Accuracy of Method and Susceptibility to Noise or Uncertainties

A limiting factor to eddy current is that its sensitivity and accuracy are dependent on the liftoff (separation) between the probe and the tube wall. Eddy current probes must be designed to fill most of the interior volume of the tube to prevent significant variation in the probe liftoff. Therefore, the tube interior must be very clean prior to testing. If a high level of fouling is present within the tube or if there is significant denting to the tube wall, the eddy current probe may produce poor readings, or the probe may not be able to pass through the tube at all.

The technique is also subject to high noise levels in certain metals with coarse microstructure, such as certain types of cast stainless steels. This should not be encountered with condenser tubes.

Dependency on Operator Skill and Repeatability

There are many factors that can affect the flow of eddy currents which consequently cause changes in the measured impedance of a coil. Defect position and orientation relative to the probe, material temperature, coupling influences, scanning speed, and liftoff are all examples of such variables that can lead to increased signal noise and false indications. Skilled inspectors are crucial to ensure that data is collected properly and interpreted accurately.

Amount of Time Required to Perform Inspection

The inspection rate will depend in part with the travel speed selected for the eddy current probe, but in general, eddy current is known for its high inspection rate. Most eddy current inspection procedure permit a testing rate of 2 to 3 tubes per minute.

Suitability of Inspection Method for Reporting

As the eddy current probe travels down each tube, its impedance response is electronically recorded along with its position in the tube. Eddy current testing software then matches this recorded data to the appropriate tube in the tubesheet map. Eddy current testing produces a wealth of information about the tube condition that can be included in reports, but the testing results are not intuitively understandable to people without backgrounds in eddy current testing. The challenge to reporting eddy current results is the task of reducing the test data rapidly into a report that can be easily understood. Over the operating history of the technology, NDE technicians have developed more intuitive reporting schemes that provide the relevant data to plant managers more simply.

Presence of Procedural Restrictions or Complications

There are no known procedural restrictions.

Remote Field Eddy Current Inspection

When the tubes are composed of ferrous materials such as carbon steel and ferritic stainless steel, traditional eddy current testing methods cannot be used. In these cases, remote field eddy current (RFEC) can be used instead. The RFEC probe consists of a transmitter coil and one or more detector coils that are wound on a bobbin. The spacing between the receiver and the detectors is usually between 2 and 4 tube diameters and is determined by the location of the "remote field zone." The remote field zone is the region of the induced magnetic field where local eddy currents are no longer the dominant factor in the field response.

To conduct RFEC, the bobbin probe is pushed through each tube. As it moves through the tube, the transmitter coil generates a magnetic field. The field passes through the tube wall, travels along the outer surface of the wall and along the tube outer diameter, and then returns through the tube wall. The detector coils register the field magnitude and phase within the remote field zone. When the RFEC probe encounters a region of wall thinning, the magnetic field is subjected to less shielding, resulting in a field path with less time delay (greater phase) and less attenuation (greater magnitude). Information about the detected field phase and magnitude can be used to detect and characterize the flaws within the tube. An illustration of the RFEC technique is shown in Figure 5-4.

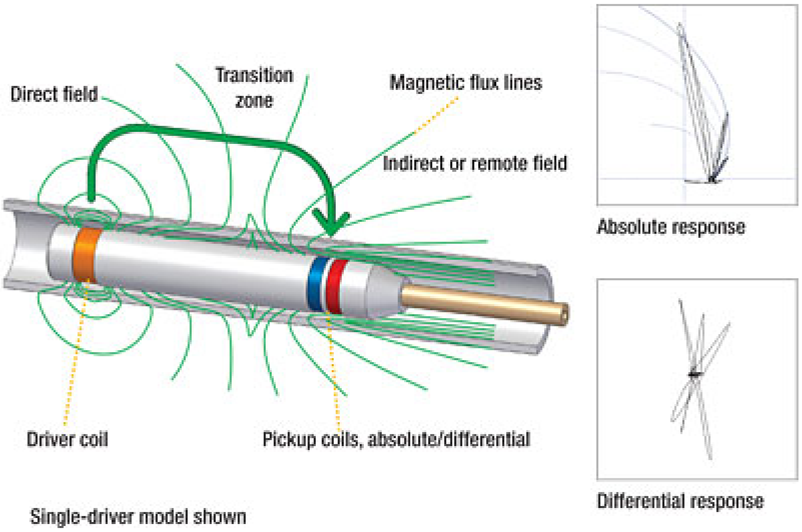

Figure 5-4
Illustration of the Remote Field Eddy Current Technique

Like standard eddy current inspection techniques, the detection sensitivity of remote field eddy current inspection systems is highly dependent on the coil design as well as the selected inspection frequencies. RFEC can detect large area discontinuities, but detection of small flaws such as pitting and cracking is difficult. Also like standard eddy current inspection of tubes, the tubes must be cleaned prior to inspection and the technology is very sensitive to geometric discontinuities.

Although RFEC is regularly mentioned in inspection materials that discuss eddy current methods for condenser tubes, the traditional eddy current techniques are preferred whenever possible because the technique is slightly faster and provides much more information about the characteristics of detected flaws.

Leak Detection Sensitivity

RFEC is considered to be ineffective at detecting small cracks and pin holes. Wall loss by erosion and corrosion can be measured once the defect depth has exceeded 20% of the wall thickness.

Ability to Provide Qualitative or Quantitative Estimation of Leak Magnitude

This method provides quantitative measurements of wall loss magnitude, but the measurement method is less quantitative than most other wall thickness measurement methods.

Accuracy of Method and Susceptibility to Noise or Uncertainties

Because RFEC relies on a far field magnetic effect, it is less susceptible to many of the uncertainties that affect traditional eddy current, but the method accuracy suffers proportionally. Because the method measures tube wall loss using a magnetic far field effect, the method tends to average the thickness of a much larger fraction of the tube, resulting in greatly reduced sensitivity to very small features and less accuracy in wall loss measurement. Also, the approach generally will not provide information regarding whether a detected flaw is located on the inner diameter or outer diameter of the tube.

Dependency on Operator Skill and Repeatability

The operator skill required to conduct RFEC testing is comparable to the skill required to conduct eddy current testing, but data interpretation tends to be more challenging and therefore requires more training.

Amount of Time Required to Perform Inspection

RFEC can typically be used to inspect 1 to 2 tubes per minute.

Suitability of Inspection Method for Reporting

RFEC generates an electronic record for each inspected tube similar to the record generated by traditional eddy current methods. The electronic records are matched to the appropriate data in the tubesheet map, and inspectors are able to generate reporting results from these electronic records. In many cases, because inspectors rely on RFEC when eddy current is not possible, inspectors will use the same reporting software and report conventions for both technologies.

Presence of Procedural Restrictions or Complications

There are no known procedural restrictions.

Tracer Gas Detection Methods

In 1978, EPRI sponsored the development of the tracer gas detection method as a means of detecting very fine leaks from condenser tubes and air inleakage from the condenser shell. The condenser shell used the “outside-in” helium spray method, where joints or seals on the shell were sprayed with helium gas. If a leak was present, the vacuum within the shell would draw the helium through the leak and into the steam-side of the condenser. Similarly, in the “inside-out” method, helium would be pumped into the interior of the condenser tubes when the tubes were accessible during partial load operation. If a leak was present within the tube, then helium would again be drawn into the steam side of the condenser. Any leaking helium gas would be collected by the non-compressible gas off-take lines and pumped out of the condenser. A mass spectrometer would be used to sample the off-take gas and determine the presence of the leak.

Using helium, the tracer gas detection method could detect helium gas concentrations in the gas off-take lines on the order of 1 part per million. Depending on the non-condensible gas off-take rate and the size of the condenser, this equates to a leak flow rate on the order of 50 gallons per day. Unfortunately, because helium is slow to diffuse, the procedure required that a high concentration of gas be pumped into each tube and then evacuated. This resulted in very long testing times for each tube and a high consumption of tracer gas. One initial solution was to use nitrogen gas to rapidly force the helium gas through the tube. The backpressure produced by the nitrogen accelerated the helium through the tube and reduced the total amount of helium that was needed to test each tube.

As the technology matured and became widely adopted, the next logical progression was to find alternative testing methods that increased the inspection speed and further improved detection sensitivity. Inspectors discovered that Sulfur Hexaflouride (SF_6) could be used as a much more effective tracer gas. Using similar testing techniques, SF_6 concentrations on the order of 1 part per 10 billion could be detected in the off-take gas, which permitted inspectors to use lower concentrations of the gas (in the form of air and SF_6 mixtures) and detect even smaller leak rates. Furthermore, SF_6 can be detected with simpler instrumentation such as a halogen diode detector probe.

At the same time, inspectors began using the plenum method to accelerate the testing method. In this method, a plenum is used to inject a short burst of tracer gas into a grid of several condenser tubes at once, perhaps starting with an area of 2 square feet. On the opposite end of the tubes, a blower or educator is used to rapidly draw the gas through the tubes. If a leak is detected, then smaller and smaller plenums are used until the leaking tube or tubes are identified. With this method, the waiting time for any residual gas to dissipate between each test is greatly diminished.

More recently, the U.S. Environmental Protection Agency has placed restrictions on the amount of SF_6 that can be consumed in the power industry, making extensive testing with SF_6 difficult. Other tracer gas compounds have been investigated, including halogenated compounds (chlorinated and fluorinated hydrocarbons) with success, but the use of many of these compounds are not only costly but have also been heavily restricted or banned due to their potential environmental effect. Inspectors have also returned to more heavy use of helium inspection techniques in conjunction with refined gas detection equipment. As a consequence, inspectors must now use less sensitive helium gas with more complicated detection electronics, work with more expensive alternative tracer gasses, or be willing to negotiate the consumption of SF_6 with the EPA.

Leak Detection Sensitivity

Helium tracer gas can be detected within the non-condensible off-gas line in concentrations of 1 part per million. Using current inspection techniques, this concentration equates to an equivalent leak flow rate of 10 Liters per day (or 10^-1 mbar*L/s). Sulfur Hexafluride tracer gas can be detected in concentrations of 1 part per 10 billion. Using current inspection techniques and air-SF_6 test mixtures, equivalent leak flow rates of less than 1 mL per day (or 10^-5 mbar*L/s) are detectable, although even smaller leak rates could be detectable.

Ability to Provide Qualitative or Quantitative Estimation of Leak Magnitude

Reasonable estimates of the leak rate from a given tube or set of tubes can be calculated by measuring the concentration of the tracer gas in the off-take line. Based on these concentration measurements, the leak rate measurement is semi-quantitative.

Accuracy of Method and Susceptibility to Noise or Uncertainties

If the tracer gas test is not conducted properly, there is a risk of contaminating the test environment with a background level of tracer gas, which may produce false signal detections until the gas sufficiently dissipates. The primary cause of background contamination during testing is insufficient waiting time between tracer gas injections.

Some of the gasses used to perform this test also exist in trace amounts within the air. The primary example is helium. The concentration of the tracer gas within the air determines the lowest possible measurement threshold for the trace gas detection method.

Dependency on Operator Skill and Repeatability

Successful application of this test method requires specific training and practice with other skilled technicians. Techniques such as the gas dispensing method, interpretation of the gas detection response, calibration of instrumentation, and the calculation of appropriate wait times between tests affect the accuracy of the method and the efficiency of the test procedure.

Amount of Time Required to Perform Inspection

The total elapsed time between initial injection of the tracer gas, detection of the gas at the off-take air ejectors, and final dissipation of any remaining tracer gas may be several minutes. This time period is subject to the size and configuration of the condenser and the requirements of the inspection. As a result, the total time required to conduct tracer inspection on the entire condenser may be prohibitive. Instead, tracer detection is more often used to find leaks when other test methods have identified the presence of a leak but has not been able to isolate the leak location.

Suitability of Inspection Method for Reporting

Using the plenum method an operator is able to recursively search for the leaking tube(s) within the bundle. Once the leak is identified, the tube or tubes are plugged. Any mapping of the bundle must be manually recorded as this method does not produce electronic reporting material.

Presence of Procedural Restrictions or Complications

The Environmental Protection Agency is placing restrictions on the use of SF_6 in the power industry, making the use of the gas for testing more difficult. Inspectors are often forced to use helium detection with the more complicated mass spectrometer instrumentation or identify other tracer gasses that have not been banned from use.

Radioactive Tracer Detection Methods

The radioactive tracer detection method is possibly the most sensitive leak detection method available for condenser inspection. Under this method, a minute amount of compatible radioisotope is injected into the condenser cooling water prior to the waterbox and allowed to flow through the condenser tubes. The injection process is rapid and brief in order to minimize the spreading of the isotope in the cooling water flow stream. A minimum of two radiation detectors are positioned along the condenser to monitor the radiation activity as it passes through the condenser. The injection detector is located on the inlet line to the waterbox to monitor the radiation activity as it enters the condenser. The leak detector is located on the condenser drain line (or drain lines) to measure the radiation activity of any radioisotope that leaked through to the steam side of the condenser. In some cases, additional detectors are positioned along the condenser to detect the radioisotope activity as it travels through the condenser. If a leak is detected, the additional information collected from these detectors can help isolate the leak location.

Detectors are shielded and collimated in order to make them unresponsive to extraneous influences. While precautions to carefully shield the detectors are taken, false peaks can still be induced from the surroundings. To filter out these false peaks a fully shielded brick detector is normally used in tandem with the leak detector. Comparing the records of the two detectors allows the operator to screen out any false indications.

After each radioactive tracer injection, the inspectors will record the radiation activity spike on the injection detector and any radiation activity spikes measured by the leak detector. Provided no significant activity is recorded by the brick detector over the elapsed time, then the leak rate can be calculated by comparing the ratio of the total activity measured by the leak detector to that of the injection detector. Using this ratio and information about the water and steam flow rates in the condenser, the aggregate leak rate can be calculated. Using this method, leak rates as small as 10^-5 mbar*L/s for an individual condenser tube can be measured.

Selection of radioactive tracers is very important to the success of the leak detection test. A radioactive tracer with sufficient gamma radiation to penetrate through the wall of the tubes should be selected. Also, a radioactive tracer with a half-life comparable to the duration of the experiment should be considered.

Table 5-1
Radioactive Tracers Commonly Used for Leak Detection in Heat Exchangers

Radioisotope	Half-life	Gamma Energy, MeV (Abundance %)	Chemical Form	Tracing Phase
Sodium 24	15 h	1.37 (100%); 2.75 (100%)	Sodium carbonate	Aqueous
Bromine 2	36 h	0.55 (70%) 1.32 (27%)	Ammonium Bromide, Methylbromide, Dibromobenzene	Aqueous Gases Organic
Iodine 131	8.04 d	0.36 (80%) 0.64 (9%)	Potassium or sodium iodide, Idobenzene, Hippuran	Aqueous Organic
Technetium 99m	6 h	0.14 (90%)	Pertechnetate	Aqueous
Indium 113m	100 min	0.392 (65%)	EDTA complex	Aqueous
Krypton 85	10.6 y	0.51 (0.7%)	Krypton	Gases
Krypton 79	35 h	0.51 (15%)	Krypton	Gases
Xenon 133	5.27 d	0.081 (37%)	Xenon	Gases
Argon 41	110 min	1.29 (99%)	Argon	Gases

Despite the extreme sensitivity of the radioactive tracer detection method, the detection method has seen far more use on heat exchangers in process engineering plants and very little use on condensers in the power industry. This may be due in part to the fact that the method requires the introduction of radioactive material into the cooling water stream and potentially into the water-steam cycle. Consequently, the now contaminated water must be managed and documented for environmental safety requirements, which may prove to be cost and time prohibitive to a power generating station. Furthermore, the current testing procedures for condensers do not permit testing methods that allow individual condenser tubes to be leak tested. As a result, while the method is effective at detecting and measuring very minute leaks, the method faces some challenges in actually locating the leaking tube. To improve the testing method, new radioisotope material handling practices must be developed that will permit the testing of individual tubes.

Leak Detection Sensitivity

The leak detection sensitivity for this method is dependent on measuring the concentration of radiation leaving the condenser through the hotwell discharge lines and comparing it to the concentration of radiation entering the waterbox. Therefore, the actual sensitivity is dependent on the condenser size, operating condition, and total number of tubes. In a typical condenser, leak rates as small as 10^-6 mbar*L/s for an individual condenser tube can be measured.

Ability to Provide Qualitative or Quantitative Estimation of Leak Magnitude

Quantitative estimates of total leak magnitude within the condenser can be calculated by comparing measured radiation activity entering and leaving the condenser.

Accuracy of Method and Susceptibility to Noise or Uncertainties

The accuracy of the radioactive tracer detection is limited by the accuracy of the information known about the operating conditions of the condenser, including the tube volumes, the condenser shell volume, the volume flow rates through both the condenser steam side and condenser tubes, and the number of active tubes. The detection efficiency of the radioactive tracer detectors will also affect the accuracy of the measurement.

Dependency on Operator Skill and Repeatability

The test repeatability is limited by the accuracy of quantity of radioactive tracer material injected into the condenser and by the consistency of the fluid flow characteristics within the condenser. In many testing procedures, multiple radioactive tracer injection tests are performed in sequence to ensure consistency of the results.

Sufficient information regarding operator skill could not be collected during the study to evaluate this metric.

Amount of Time Required to Perform Inspection

Under currently accepted testing procedures, radioactive tracer injection is only permitted prior to each waterbox. The actual duration of a single radioactive tracer test is calculated based on operating specifications of the condenser and is usually on the order of a few minutes. The test is usually repeated for each test setup. The majority of testing time is dedicated to instrument calibration prior to testing and pre-test setup activities.

Suitability of Inspection Method for Reporting

This method does not typically produce electronic records of the test results. Written records must be prepared to document the test results.

Presence of Procedural Restrictions or Complications

The inspection method appears to have been met with resistance in the power generation industry due to its use of radioactive materials. Furthermore, it does not appear than many inspection vendors plan to be equipped to perform this type of service. Therefore, the awareness of this testing approach among plant operators is low.

6

SUMMARY OF FINDINGS

The leak detection technologies used in the power industry for condenser tube inspection tend to fall into one of three categories. The first category consists of online chemical monitors that are installed within the circulating water flow loop and within the condenser itself. Although these sensors cannot identify the source of a leak, they usually provide the first indication to plant operators that a leak has occurred. The second category consists of technologies that are less suited for actually identifying leaks and more suited locating and characterizing tube damage that may eventually lead to a leak. The third category consists of inspection technologies that are designed to detect and locate already leaking tubes.

Although each operating plant may rely on different combinations of specific inspection technologies, the sequence of inspections follow a common pattern. The industry as a whole has espoused a philosophy of preventative maintenance and inspection. In the past, condenser inspection was reactive. If the presence of a leak was detected, then the cause of the leak was identified and repaired. Now, condenser inspection favors proactive identification of tubes that are at risk of leakage. As a result, inspection programs now favor technologies that can characterize tube damage and identify tubes that are at risk of leaking over technologies that identify already leaking tubes. The inspection methods that are used to identify the severity of damage within tubes include:

- Visual inspection – tubesheet inspection, internal inspection, and videoscope inspection
- Eddy current inspection – traditional eddy current and remote field eddy current
- Internal Rotary Inspection System (IRIS)
- Guided Wave Testing – Ultrasonic Guided Wave and Acoustic Pulse Reflectometry

Eddy current testing is the most widely accepted method for inspecting tubes and for generating records the tube condition. Visual inspection is also very prevalent across the industry, but not all plants are willing to rely on formal visual inspection records for determining the condition of the condenser. For the most part, inspection programs developed around preventative inspection practices have proven successful, and the number of tube failures throughout the industry has diminished through time.

If a tube failure does occur between planned condenser inspections, or if the primary inspection techniques fail to identify a leaking tube, then the water chemistry monitors installed within the plant circulating water loop usually provide the first indication of cooling water in-leakage. As cooling water enters the plant water cycle, the concentration of contaminants rises. Eventually, the concentration of contaminants in the water cycle will rise above the monitors’ threshold of detection and the presence of a leak will be identified. If the leak is not addressed, then the contaminant level may continue to rise to a critical level and force a plant shutdown.

If a leak is detected, then plant operators use one of the previously described leak detection methods to identify the source of the leak. Some leak detection methods can be applied under reduced load condition, where the condenser remains in operation with one or more waterboxes removed, while other detection methods require complete shutdown of the condenser to be conducted.

The identified leak detection methods include:

- Methods requiring reduced load operation:
  - Soap or Foam Testing
  - Dimple Plug Testing
  - Acoustic Leak Detection (under vacuum)
- Methods that require complete shutdown:
  - Tube Drip Test
  - Hydrostatic Fill Test
  - Acoustic Leak Detection (pressurized tube)
  - Acoustic Tone Detection
  - Acoustic Pulse Reflectometry
  - Photoacoustic Gas Detection Method
- Methods that are applicable under both conditions:
  - Pressure Decay Test (either with tube pressurized or with shell drawing vacuum)
  - Traditional Eddy Current Testing
  - Remote Field Eddy Current Testing
  - Ultrasonic Guided Wave Testing

Figure 6-1 illustrates the relative leak detection sensitivities of each of the above methods. The equivalent leak rated required to detect water in-leakage rates of 1 to 2 gallons a day is marked as a vertical red line. Technologies with the greatest sensitivities are indicated by a lower detectable leak rate (to the right side of the chart).

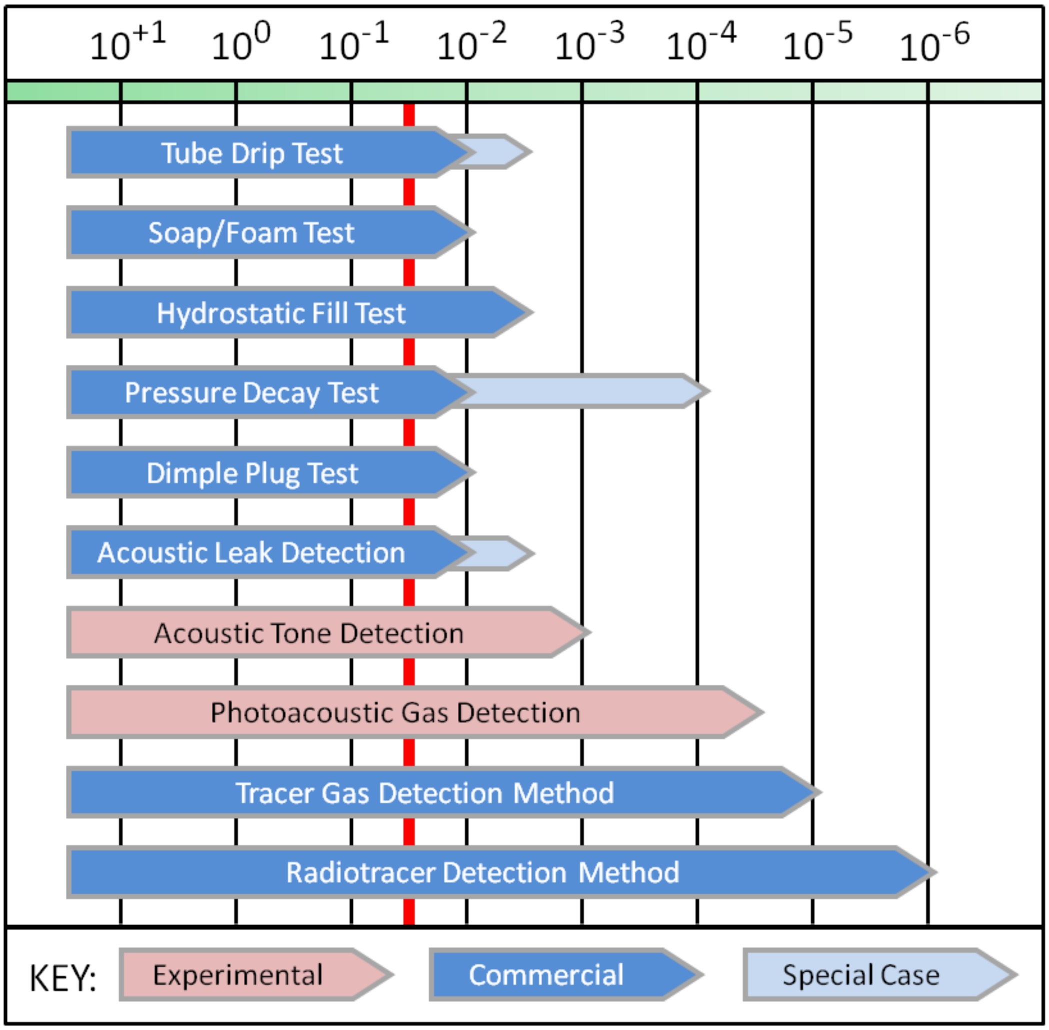

Figure 6-1
Equivalent detection sensitivity in mbar*L/s for the identified leak detection technologies.

As indicated by Figure 6-1, all of the accepted leak detection methods have the capability of detecting the target leak rate. Therefore, for a target leak rate of 1 gallon a day, selection of the appropriate leak detection method is less dependent on the method's detection sensitivity and more dependent on the operating demands of the plant. Factors such as the plant operating conditions, the cooling water composition, the budget allocated for inspection, and the amount of time the plant can remain in either a reduced load or shutdown state will determine the inspection method that is selected. For example, some plants are able to use the hydrostatic fill test to check for leaks during each outage. This test is very simple and relatively quick to implement because it simply involves filling the condenser shell with water and then checking the tubesheet for weeping tubes. Although it is a fast, simple, and inexpensive method, this test is not applicable to most modern condensers because most condenser shells cannot withstand the stress applied by the water. Assuming the leak detection sensitivity of the existing inspection methods is acceptable to plant operators and industry regulators, then future improvements to the existing technologies may be focused on reducing the expense and time related to performing the inspections and improving training in the application of the methods.

7

CONCLUSIONS

According to the industry professionals surveyed as part of this study, the modern condenser tube inspection programs have been very successful at minimizing the potential damage caused by condenser tube cooling water in-leakage. The industry relies on three categories of inspection technologies to prevent tubes from leaking and eliminate tubes that do leak. These three categories are technologies that characterize the damage extent in tube, technologies that measure the amount of contaminants entering the plant circulating water through in-leakage, and technologies that detect and locate leaking tubes.

Within the first category, there are four recognized groups of inspection technologies that are capable of detecting the severity of damage within the tubes:

- Visual inspection – tubesheet inspection, internal inspection, and videoscope inspection
- Eddy current inspection – traditional eddy current and remote field eddy current
- Internal Rotary Inspection System (IRIS)
- Guided Wave Testing – Ultrasonic Guided Wave and Acoustic Pulse Reflectometry

Of these, Eddy current testing is the most widely accepted method for inspecting tubes and for generating records the tube condition. Visual inspection is also very prevalent, but inspection records generated by visual techniques are not relied upon as heavily as the eddy current records.

In the event that a tube failure does occur, then the water chemistry monitors installed within the plant circulating loop usually provide the first indication of cooling water in-leakage. Once leakage is detected, inspectors may use one of several commercially available leak detection methods to identify and locate the leaking tube. The identified leak detection techniques that are in commercial use are summarized in Table 7-1.

Figure 7-1
Commercially Available Condenser Tube Leak Detection Technologies

Leak Detection Technique	Detection Sensitivity (mbar*L/s)	Qualitative / Quantitative	Inspection Time Commitment	Operator Skill Level
Tube Drip Test	10^-2	Qualitative	N/A	Visual inspection training
Soap or Foam Test	10^-2	Qualitative	~10 min/m^2 of tubesheet	Basic method training
Hydrostatic Fill Test	5x10^-3	Qualitative	~1-2 days total	Basic method training
Pressure Decay Test	10^-2	Quantitative	~2 min/tube	Basic method training
Dimple Plug Test	10^-2	Qualitative	~1-2 days total	Basic method training
Acoustic Leak Detection	10^-2	Semi-Quantitative	Unknown	Extensive experience required
Tracer Gas Detection	10^-5	Quantitative	Varies widely per Requirements (~3-5 min/test)	Advanced training and experience required
Radioactive Tracer Detection	10^-6	Quantitative	~1 day total	Advanced training and experience required

Although many of these techniques have seen improvements over the past decade or so, the basic inspection practices have not changed significantly in the past 30 years. In the cases where water in-leakage is detected, plant operators will usually choose to inspect the condenser using one of these methods. Depending on the leak rate, operators must choose between applying one of the simpler leak detection techniques or whether it is necessary to use more involved inspection techniques. From Table 7-1, it is apparent that in order to achieve greater detection sensitivity, more highly trained inspectors and more sophisticated inspection equipment is needed.

Based on the responses of plant operators and the defined target leak detection sensitivity of 10^-2 mbar*L/s (about 1 gallon per day) defined in this study, the detection capabilities of the current inspection practices appear to meet the current industry needs. Even though all technologies meet the leak detection threshold, many of the technologies are only able to achieve this detection sensitivity under best operating conditions. In the actual inspection conditions of the plant, unexpected noise conditions or complications to the inspection procedure often reduce the effective detection sensitivity. Although all of these technologies are capable of detecting 1 gallon per day leaks, industry professionals have indicated that the realistic leak detection capabilities for the more basic techniques tend to be lower, perhaps 10 gallons per day.

Based on the philosophy of preventative maintenance and inspection, most plant managers now espouse a policy of zero leak tolerance. If plant operators wish to ensure that even the smallest leaks are detected, then their best option is to use gas detection methods to locate leaking tubes. Unfortunately, because this inspection technique tends to be intensive and time consuming, operators will usually rely on this technology only when there is already evidence of a leak. The radioactive tracer detection method is also suitable for finding very small leaks, but the availability of the gas detection method and the procedural restrictions imposed on the radioactive tracer technique has suppressed its market presence in the power generating industry.

If plant operators and industry regulators determine that condensers must be screened more extensively for leaks on the order of 1 gallon per day, then there may be a need for further development in the industry's leak detection capabilities. Some of the existing leak detection methods could be further refined, or a new method could be developed. To be accepted for large scale screening of condensers, a new or updated technique must be able to demonstrate greater detection sensitivity and must not require significant amounts of time to conduct. Ideally, a new or refined technique would also be easy to conduct, would be less sensitive to the common environmental noise factors, and would not require extensive equipment and training to conduct. Such a technique could be developed by further refining one of the existing commercially available inspection techniques, by developing a new technique from one of the identified experimental techniques, or by investigating new approaches to leak detection.

8
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