Developments in Steam Generator Leak Detection at Ontario Hydro

Kevin J. Maynard and Vic P. Singh

ABSTRACT

A method for locating small tube leaks in steam generators has been developed and implemented at Ontario Hydro. The technique utilizes both helium leak detection and moisture leak detection. The combination of these two methods allows tube leaks to be detected in any part of the tube bundle, including those submerged below water near the tubesheet. The estimated detection limits for the helium and moisture leak detection systems are 0.001 kg/hr and 0.05 kg/hr respectively, expressed as leak rates measured at typical boiler operating conditions. This technology is best utilized in situations where the leak rate under operating conditions is smaller than the practical limit for fluorescein dye techniques (~2 kg/hour). Other novel techniques have been utilized to increase the reliability and speed of the boiler leak search process. These include the use of argon carrier gas to stabilize the buoyant helium gas in the boiler secondary.

Ontario Hydro Technologies
800 Kipling Avenue
Toronto, Ontario
M8Z 5S4
CANADA

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INTRODUCTION

Leaks in steam generator (SG) tubes are a costly source of capacity loss in nuclear generating facilities. Often, large leaks (>1 kg/hr) are located during an outage with pressurized dye solution. In the so-called 'fluorescein method', a pressurized fluorescein dye solution in the boiler secondary leaks through to the primary side. Tube leaks are then located by a manual visual inspection of the primary side tube sheet with the aid of a black light to illuminate the dye stain. Experience has shown that the practical sensitivity limit for the fluorescein method is approximately 1 kg/hr, measured at typical SG operating conditions. For SG leaks smaller than this limit, other methods are usually applied.

Due to the difficulty in locating small boiler leaks with the fluorescein method, a more sensitive leak detection technique was sought and developed for field use on Ontario Hydro's CANDU‡ Units. This paper describes the particular leak detection system which was recently developed at Ontario Hydro Technologies (OHT). The technique involves helium leak detection, an established method for locating leak paths in a wide variety of industrial and commercial applications, including boilers [1]. Several enhancements have been incorporated to provide a more complete and efficient inspection and the main ones are reported here. The most important of these is a moisture leak detection capability, to allow detection of through-wall tube defects near the SG tube sheet. Such defects, which are often submerged below water in the boiler secondary, remain unobservable by helium leak detection, but observable with moisture leak detection. Other features include a means of stabilizing the helium gas in the boiler shell, using argon as a carrier gas. Due to the propensity of buoyant helium to flow and diffuse away from the boiler tube bundle, this feature proves to be important.

Helium leak detection has an estimated sensitivity of 0.001 kg/hr, expressed in terms of leak rate under typical CANDU operating conditions. These conditions are approximately $T_{inlet} =$ 300°C and $\Delta P =$ 5MPa. The helium tracer gas is completely inert and does not pose any boiler or reactor chemistry consequences. Moisture leak detection has an estimated sensitivity of 0.05 kg/hr under the same conditions expressed above.

‡ CANada Deuterium Uranium

LEAK DETECTION METHODS

Overview

Helium leak detection applied to steam generators involves the detection of helium gas leaking across the primary-secondary boundary of the boiler. In the OHT system, a leak search proceeds as follows. The boiler is first drained of water on both the secondary and primary sides. The complete secondary system is then pressurized with air, followed by a 'charging' of helium and carrier gas (usually argon) mixture into the boiler shell. The helium/argon mixture displaces the air and the tube bundle becomes 'submerged' in helium gas. With the secondary side pressurized, helium and/or residual water in the boiler secondary flows through the leak path to the primary side. The primary side of the tube bundle is continually purged with dry air so as to flush any helium gas and/or water vapor toward a detector probe placed in the primary head of the boiler. A "sniffer" probe is positioned within the primary head and is manipulated by a robotic arm around the tube sheet. The sniffer samples the air from each tube in the boiler and both helium and moisture detectors measure the concentrations in this air. A leaking tube is signaled by a helium and/or water concentration statistically above background levels.

The leak detection equipment is composed of several sub-systems installed at various points on the steam generator. These sub-systems are shown in Figure 1. The particular implementation shown reflects a typical SG design (i.e. integral steam drum) but is applicable to other SG/HX designs as well. Adapting the equipment to other facilities involves the construction of several SG-specific fittings. At the boiler primary head are located the purge and tube sheet sampling systems. The robotic arm for probe positioning is installed in either the boiler outlet (cold leg) or inlet (hot leg) side. The systems installed on the boiler secondary include a helium analyzer, a helium injection system and a control system. Each of these systems is discussed more fully in sections below.

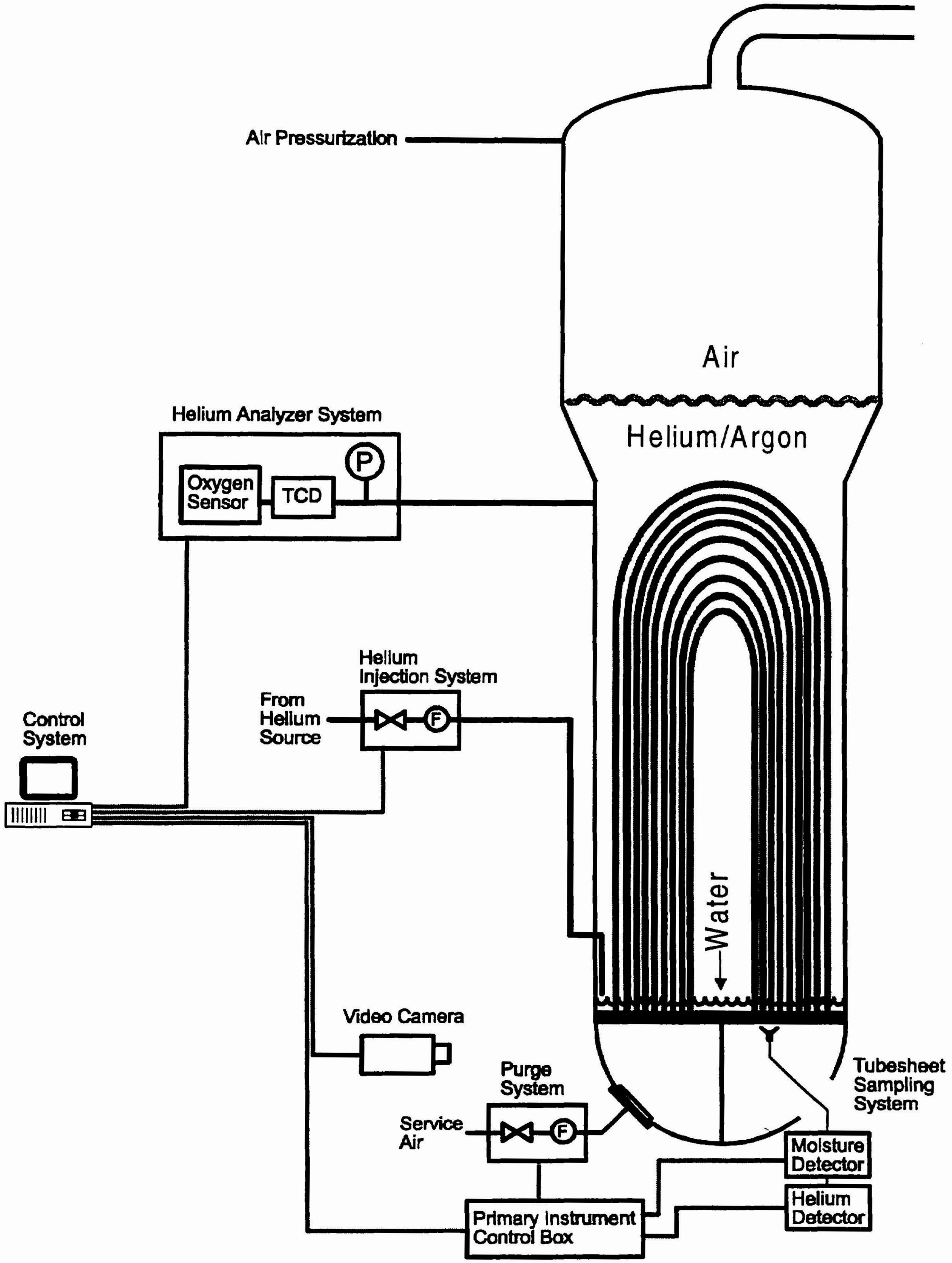

Figure 1. Overview of the major components of the SG leak detection system.

Detector Characteristics

In preparation for a leak search, the boiler secondary is drained of water to the best possible extent. However, at the tube sheet, several inches of water may remain which are difficult to completely remove. To detect tube leaks at any point in the tube bundle, including ones below the water line near the tube sheet, the leak detection system is equipped with two different methods of detection. The helium leak detector is a very sensitive instrument which detects any helium gas leaking through from the pressurized secondary side. In cases where the through-wall defect is above water, helium will readily flow through the leak path to the primary side and be detected. For leaks below water however, the helium cannot easily permeate the water layer and such leaks remain undetected by this method. The second detector, a moisture sensor, measures the primary side water concentration in the air from the tube under inspection. For leaks located under water, moisture from the secondary flowing through to the primary side will evaporate, registering as a rise in water concentration (increase in dew point). For leaks above water, the moisture sensor may also register an elevated reading, depending on the humidity and leak rate of the gas in the boiler secondary. Table 1 summarizes these characteristics.

Table 1. Characteristics of helium and moisture detectors.

Detector Type	Detects Leaks Above Water	Detects Leaks Under Water
Helium	Yes	No
Moisture	Maybe	Yes

From these characteristics, it is evident that a leak indication which registers *only* an elevated moisture content must be submerged under water. For cases where a helium indication is measured, the leak ***must be*** above water, regardless of the moisture reading.

Detection Limits

Detection limits are most useful when conveyed in terms of leak rate under typical SG operating conditions. It is this leak rate which is used as the basis for deciding if or when a boiler is to be removed from service for inspection and repair. For example, if a given leak detection technique has a quoted detection limit of 1 kg/hr under operating conditions, then a leak of this magnitude on an operating boiler should be successfully located once the boiler has been removed from service. Due to the different boiler pressure and temperature conditions present under operation and during a leak search, leak rates are not directly comparable. The

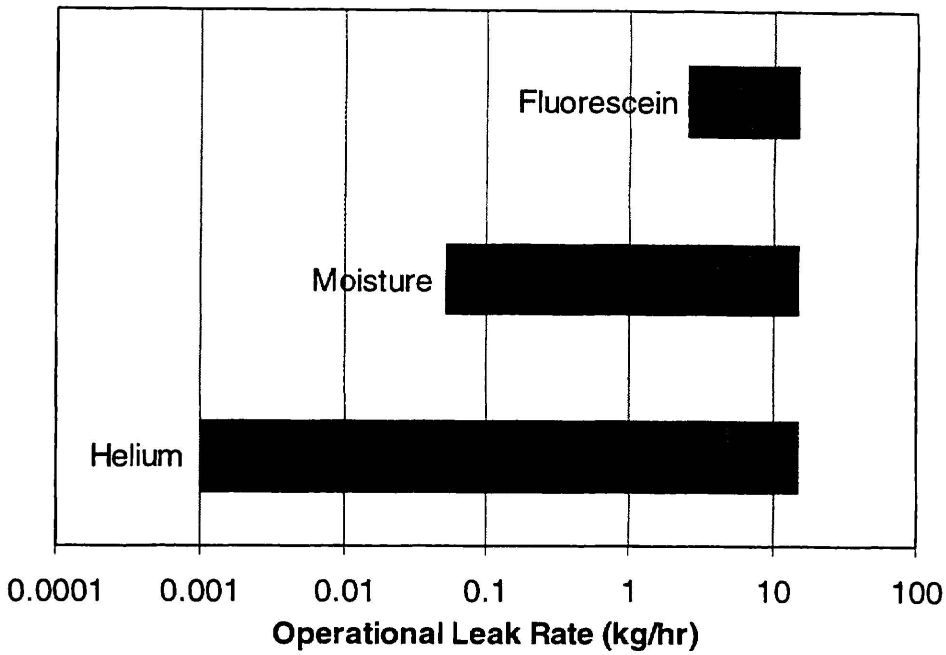

Figure 2. Summary of estimated detection limits for leak detection methods.

leak rate from a given tube under operating conditions will usually be much larger than the same tube under leak search conditions. This is due in part to thermal expansion effects and to the difference in pressure gradient across the leak path. Taking into account factors including the helium detector sensitivity and the correlation between leak rates under various conditions, [2] an operational detection limit of 0.001 kg/hr is obtained for helium leak detection. In other words, boiler leaks of this magnitude or larger under operating conditions have a high probability of being located with helium leak detection. Likewise, the estimated moisture detection limit is approximately 0.05 kg/hr, in operational units. Hence, helium leak detection is roughly 50x more sensitive than moisture leak detection. Both these methods are much more sensitive than the fluorescein method, with an estimated sensitivity of 2 kg/hr. The detection limits are summarized in Figure 2. These detection limits are not intended to be quantitative, but merely estimates which may prove useful in the application of this technology. They have been specifically calculated at typical CANDU operating conditions of $T_{inlet} =$ 300°C and $\Delta P =$ 5MPa.

Helium Buoyancy Control

For a successful leak search, the helium in the boiler secondary must remain there for the duration of the test. Given the fact that the secondary system *is not* uniformly filled with the same concentration of helium (i.e. the steam drum and steam line contain only air), there are several means by which helium escapes from the boiler. Helium is a light gas which, due to buoyant forces, tends to rise when placed in air. Its small atomic weight also contributes to relatively large diffusion rates in air. There is also the possibility that convection currents and eddies within the boiler can cause bulk flow of helium away from the region surrounding the tube bundle. Therefore, maintaining a uniform helium charge in the boiler secondary poses difficulty. The use of diaphragms or baffles to isolate the boiler from the remainder of the secondary system is undesirable for several reasons, including the need for steam drum entry and possible boiler modifications. However, if helium is pre-mixed with a heavy carrier gas, the mixture can be made negatively buoyant in air which permits it to remain fixed within the boiler secondary. Using a heavy carrier gas also limits the diffusion rate of helium from the boiler. The most suitable heavy carrier gas is argon, because of its chemical inertness and relatively abundant supply. Since no significant amount of the argon added to the boiler can migrate into the primary side, activation of the argon to Ar-41 is not a possibility. Although argon is not chemically toxic, it is an asphyxiant and therefore poses a hazard in confined spaces. In situations where boiler isolation and buoyancy are less problematic, air may be a suitable alternative to argon.

Phased Leak Search

The leak search is divided into two phases- tube sheet survey followed by single tube inspections. The survey covers all of the tube sheet and is intended to localize the leak(s) within a subsection of the tube sheet. The survey is conducted using a multi-tube funnel fitted to the end of the robotic manipulator arm. If a leaking tube is among the tubes being sampled, a leak signal is registered (flagged) for closer examination in the single tube inspections. The funnel is moved across all of the tube sheet in an organized pattern, with each measurement taking approximately 30 seconds. Using this method, a boiler containing thousands of tubes may be completely surveyed within 24 hours.

Following the leak survey described above, the single tube inspections commence. Their purpose is to find the leaking tube within the subsection(s) already located in the survey. This segment of the leak search is performed with a single tube sniffer probe. Each tube in the flagged subsection is individually checked by moving the sniffer probe in close proximity to the tube sheet plane at the tube exit. The leak detector signal is recorded for each tube before moving to the next tube. Once the leaking tube has been located, its identity is carefully confirmed by noting the readout of the robotic arm position as well as noting the relative position of nearby landmarks on the tube sheet. A marking tool attached to the robotic arm may also be used to apply a paint mark to the identified leaking tube, as an aid to further inspection or repair activities.

LEAK DETECTION EQUIPMENT

Primary Subsystems

Purge System

An air purge system is installed near the primary head of the boiler under test to purge the whole tube bundle with dry air (see Figure 1). It consists of a gas manifold to regulate and measure air flow into the boiler through the manway. The boiler manway is sealed with a baffle plate to provide a slight pressurization of one side of the boiler bowl which establishes a small air flow through each of the boiler tubes. The air purge direction may be from the primary outlet toward the primary inlet, or vice versa depending on convenience. The purge manifold also contains a 'simulated leak' apparatus, consisting of a small cylinder containing a helium/argon mixture of known concentration. A small stainless steel tube from the cylinder is installed into one of the boiler tubes through a hole in the manway baffle. A small flow of helium gas can be introduced into this tube to act as a diagnostic aid for the helium leak detector installed near the other side of the boiler bowl (to be described below). The purge manifold is connected to an instrument control box, which routes all control and data signals back to a central control system outside the boiler area.

Tube Sheet Sampling System

At the opposite primary manway to the purge system is located the tube sheet sampling system. This consists of a sampling sniffer probe which is manipulated according to a predetermined pattern across the tube sheet in search of helium gas or water vapor leaking through from the secondary side. The gas sample from each boiler tube is routed to the helium and moisture detectors. The helium detector is a commercial mass spectrometer instrument contained within a purged enclosure. The purpose of the enclosure is to isolate the sensitive instrument from ambient helium around the boiler. The moisture detector (dew point meter) is connected in series with the helium detector. As with the purge system, all signals are routed through an instrument control box to the central control system. Facility is made for a video camera to be installed near the boiler primary head to remotely monitor the equipment setup and operation.

Sniffer Probe

The sniffer probe is manipulated remotely across the tube sheet by a robotic arm (such as Zetec SM-23). No primary head boiler entries are required to completely inspect the boiler. The probe is essentially a funnel which is placed very near to the bottom face of the tube sheet. A slight suction draws an air sample from the tubes above the funnel down through a hose into the detectors. Various sizes of funnels have been constructed to inspect groups of tubes simultaneously, thus speeding the inspection process. For boilers with a triangular matrix of tubes, the optimal funnel sizes are fitted for 1, 7 and 19 tubes. The choice of funnel size involves a trade-off between inspection speed and sensitivity. A small funnel samples from a few tubes, thereby providing good sensitivity but with many inspections being required to cover the whole tube sheet. A large funnel provides fast inspection, but with lesser sensitivity because the gas sample from any one "leaker" tube is diluted from many non-leakers under the same funnel.

Secondary Subsystems

Helium Injection System

The pressurization of the secondary side is achieved with a combination of air and helium/argon mixture. This is due to the large volume of gas required to initially pressurize the whole secondary system and to maintain that pressure throughout the leak search. The air is first used to pressurize the complete secondary system (boiler shell, steam drum, steam lines plus ancillary systems), then the helium/carrier mixture is added to the boiler under test (see Figure 1). An air compressor, or some other means of pressurization, is attached to some portion of the boiler secondary system to provide the needed pressure (approximately 500 kPa). The compressor attachment point is preferably on the main steam outlet or near the top of the steam drum. This is to ensure that air leakage through the main steam shutoff valves will not disturb the helium gas charged within the boiler shell. A compressor attachment point near the boiler bottom would result in substantial dilution of the helium gas with air. A helium injection system is attached to the boiler blowdown system to allow helium injection into the ***bottom*** of the boiler shell. The injection system is essentially a high capacity gas manifold which can regulate and, if necessary, mix the injection gases. Due to the large volume of gas required to fill the secondary shell of the boiler it is most convenient to use premixed helium/carrier gas from a tube trailer. The injection of gas into the boiler is more time consuming and labor intensive if individual gas bottles are used.

Helium Analysis System

It is important to monitor the helium concentration in the boiler secondary during the leak search because of mass transfer processes (e.g. diffusion, convection) which may result in helium dispersal. To confirm the presence of sufficient helium gas in the boiler secondary, a helium analysis system is used. The system functions by drawing a sample of the boiler secondary gas through an automated thermal conductivity detector (TCD) to measure helium content and an oxygen sensor to measure oxygen content in the boiler. The gas sampling line is attached to the boiler secondary through a suitable access point such as a blank flange or boiler level instrumentation. Ideally, the sampling point should be placed at an elevation near the top of the tube bundle to ensure that the whole bundle is completely 'bathed' in helium gas. As with the other subsystems, the helium analysis module is remotely controlled by the central control system.

Control System

Due to the fact that the various leak detection subsystems are installed at different locations on the SG, a central control system is a necessity. Ideally, the control system should be located near to the robotic arm control, due to the need for continual interaction between the leak detection and robotic arm operators during the leak search. All subsystems are connected electronically to the control system with signal cables routed to each of the remote locations. To eliminate the effects of noise and ground loops, the signals between the sub-systems and central control were designed to be completely digital. The heart of the control system is a PC fitted with an RS-485 interface card, permitting high speed, digital communication. The PC software for the control system allows logging of all process parameters on a continuous basis, as well as operator directed control of remote devices such as valves and flow controllers. The helium and dew point signals are graphed on screen so that trends can be discerned by the operators. Other software screens allow the status of all sub-systems to be observed and changed at will.

ALTERNATE LEAK SEARCH STRATEGY

By using *only* moisture leak detection, a somewhat less sensitive but simplified leak search may be conducted. With the boiler secondary kept filled with *water* instead of drained and filled with helium gas, leaks in any part of the tube bundle will transmit liquid water to the primary side. This will then be detected with the moisture sensor, as before. The advantage of the 'Moisture Only' mode is the simplified prerequisite process, since some equipment and materials specific to helium leak detection are not required. The disadvantage of this mode is the loss of sensitivity relative to helium leak detection. The choice between 'Moisture Only' mode and 'Helium & Moisture' mode must be based on considerations such as the boiler leak rate, schedule and economic factors. Table 2 below provides a comparison of these two modes of leak detection.

Table 2. Prerequisites and properties of the two leak detection modes.

Prerequisite	**Helium & Moisture**	**Moisture Only**
Detection Limit (kg/hr)	0.001	0.05
Primary air supply required	Yes	Yes
Robotic arm required	Yes	Yes
Primary Subsystems installed	All	Partial
Boiler pressurization required	Yes	Yes
Helium supply required	Yes	No
Boiler drained for leak search	Yes	No
Injection system required	Yes	No
Helium analyzer required	Yes	No

CONCLUSIONS

The leak detection technology described herein has been utilized successfully on several occasions at Ontario Hydro CANDU facilities in the past year to locate small boiler leaks. The use of both helium and moisture detection capabilities was found to be essential for a complete leak search on all regions of the tube bundle. The helium concentration in the boiler secondary remained stable throughout the leak search period, confirming the usefulness of the argon carrier gas. An estimated leak rate detection limit of 0.05 kg/hr was deduced for the moisture detection capability, referenced to typical CANDU operating conditions. The corresponding detection limit for helium detection is approximately fifty times better (0.001 kg/hr).

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