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CURRENT PRACTICE AND DEVELOPMENTAL EFFORTS FOR LEAK DETECTION IN U. S. REACTOR PRIMARY SYSTEMS*

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ABSTRACT

Current leak detection practices in 74 operating nuclear reactors have been reviewed. Existing leak detection systems are adequate to ensure a leak-before-break scenario in most situations, but no currently available, single method combines optimal leakage detection sensitivity, leak-locating ability, and leakage measurement accuracy. Simply tightening current leakage limits may produce an unacceptably large number of unnecessary shutdowns. The use of commercially available acoustic monitoring systems or moisture-sensitive tape may improve leak detection capability at specific sites. However, neither of these methods currently provides source discrimination (e.g., to distinguish between leaks from pipe cracks and valves) or leak-rate information (a small leak may saturate the system). A field-implementable acoustic leak detection system is being developed to address these limitations.

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1. BACKGROUND

No currently available single leak-detection method combines optimal leakage detection sensitivity, leak-locating ability, and leakage measurement accuracy. For example, although quantitative leakage determination is possible with condensate flow monitors, sump monitors, and primary coolant inventory balance, these methods are not adequate for locating leaks and are not necessarily sensitive enough to meet regulatory-guide goals. The technology is available to improve leak detection capability at specified sites by use of acoustic monitoring or moisture-sensitive tape (MST) [1]. However, current acoustic monitoring techniques provide no source discrimination (e.g., to distinguish between leaks from pipe cracks and valves) and no leak-rate information (a small leak may saturate the system). MST provides neither quantitative leak-rate information nor specific location information other than the location of the tape; moreover, its usefulness with "soft" insulation needs to be demonstrated.

2. REVIEW OF CURRENT PRACTICE

U.S. Nuclear Regulatory Commission Guide 1.45 [2] recommends the use of at least three different detection methods in reactors to detect leakage. Monitoring of both sump-flow and airborne-particulate radioactivity is mandatory. A third method can involve either monitoring of condensate flow rate from air coolers or monitoring of airborne gaseous radioactivity. Although the current methods used for leak detection reflect the state of the art, other techniques may be developed and used. Regulatory Guide 1.45 also recommends that leak rates from identified and unidentified sources be monitored separately to an accuracy of 1 gal/min, and that indicators and alarms for leak detection be provided in the main control room.

Since the recommendations of Regulatory Guide 1.45 are not mandatory, the technical specifications for 74 operating plants including PWRs have been reviewed by the present authors to determine the types of leak detection methods employed, the range of limiting conditions for operation, and the surveillance requirements for the leak detection systems.

All plants use at least one of the two systems specified by Regulatory Guide 1.45: All but eight use sump monitoring, and all but three use particulate monitoring. Monitoring of condensate flow rate from drywell air coolers and monitoring of atmospheric gaseous radioactivity are also used in many plants.

The allowed limits on unidentified coolant leakage are shown in Fig. 1 (upper panel). The limit for all PWRs is 1 gal/min, whereas the limit for most BWRs is 5 gal/min. The limits on total leakage (Fig. 1, lower panel) are generally 10 gal/min for PWRs and 25 gal/min for BWRs. (Regulatory Guide 1.45 does not specify leakage limits, but does suggest that the leakage detection system should be able to detect a 1-gal/min leak in 1 h.) In some cases, limits on rates of increase in leakage are also stated in the plant technical specifications. Two BWRs have a limit of 0.1 gal/min/h; four have a limit of 0.5 gal/min/h.

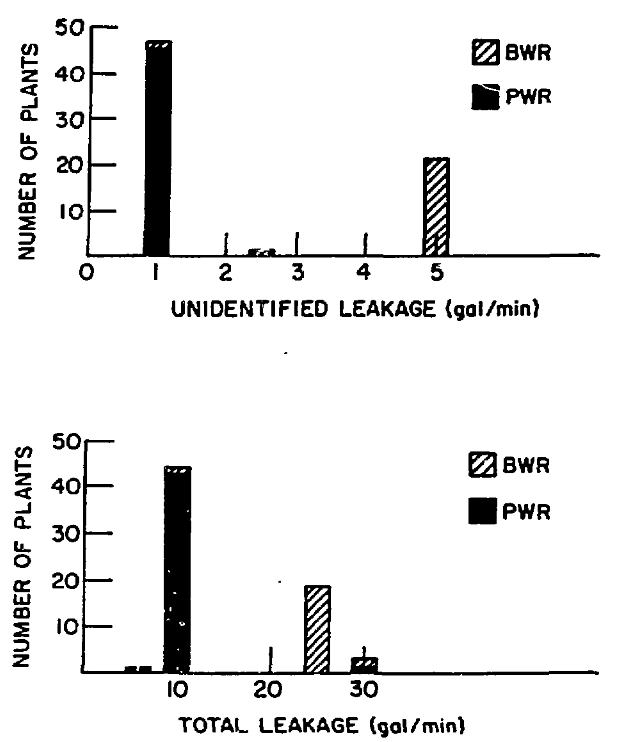

Figure 1. Amounts of Unidentified and Total Coolant Leakage Allowed at BWRs and PWRs. Conversion factor: 1 gal/min = 3800 cm^3/min.

Generally speaking, reactor operators rely on sump pump monitoring to establish the presence of leaks. Other methods appear to be less reliable or less convenient. In most reactors, the surveillance periods are too long to detect a 1-gal/min leak in 1 h, as suggested by Regulatory Guide 1.45, but it appears that this sensitivity could be achieved if monitoring procedures were modified. Simply tightening the current leakage limits to improve sensitivity is not adequate,however, since this might produce an unacceptably high number of spurious shutdowns owing to the inability of current leak detection systems to identify leak sources. None of the systems provides any information on leak location, and leaks must be located by visual examination after shutdown. Since cracks may close when the reactor is shut down, reducing flow rates considerably, it would be desirable to be able to locate cracks during plant operation.

The estimated sensitivity of leakage monitoring is occasionally addressed in the technical specifications for reactors. For example, one specification indicates that air particulate monitoring can, in principle, detect a 0.013-gal/min leak in 20 min, that the sensitivity of gas radioactivity monitoring is 2-10 gal/min, and that the sensitivity of condensate flow monitoring is 0.5-10 gal/min. Continuous sump pump monitoring appears capable of detecting a 1-gal/min leak in 10-60 min.

Although current leak detection systems are adequate to ensure a leak-before-break scenario in the great majority of situations, one must also consider the possibility that large cracks may initially produce only low leak rates. This situation could arise because of corrosion plugging or fouling of relatively slowly growing cracks or the relatively uniform growth of a long crack before penetration. In such cases, the time required for a small leak to become a significant leak or rupture could be short, depending on crack geometry, pipe loading, and transient loading (a seismic or water hammer event).

The shortcomings in existing leak detection systems are not simply a matter of conjecture. The Duane-Arnold safe-end cracking incident [3] indicates that the sensitivity and reliability of current leak detection systems are clearly inadequate in some cases. In the Duane-Arnold case, the plant was shut down on the basis of the operator's judgment when a leak rate of 3 gal/min was detected; however, this leakage rate is below the required shutdown limit for almost all BWRs. Examination of the leaking safe-end showed that cracking had occurred essentially completely around the circumference. The crack was throughwall over about 20% of the circumference and 50-75% throughwall in the non-leaking area.

In order to improve detection of leaks through intergranular stress corrosion cracks (IGSCCs), some U.S. utilities have installed either acoustic emission monitors (AEMs) or MST at specific welds. The AEMs have been installed at reactors in the Midwest and Southeast; MST has been installed by several other utilities. In general, these devices are installed near welds that have unrepaired crack indications or a weld overlay, and on nonconforming welds (those which have not received ultrasonic inspection because of high radiation levels or inaccessibility).

At one plant, endcap welds on a 22-in. pipe manifold are being monitored with a total of 16 MST sensors, some on the top and some on the bottom of the pipe. The system is checked during each 8-h shift to verify that the equipment is operating properly. At another reactor, MST is being used to monitor between 15 and 30 welds in the jet pump risers, the main recirculation line, and the RHR (residual heat removal) system piping. The primary concern at present is false alarms. The utility is committed to shutdown if the MST alarm goes off and the response is not confirmed to be a false alarm. During start-up, one MST sensor in the vicinity of a leaking valve triggered an alarm. This indicates adequate system sensitivity, but it also points out the need for quantitative information regarding leak characterization, location, and flow rate. In this specific case, it should be pointed out that flow rate information was acquired through sump pump monitoring, as the leak was quite large.

An AEM was installed in 1983 at a manifold sweepolet weld in the Georgia Power Co. Hatch reactor. This system includes a waveguide and commercially available components. No leak has been indicated by this AEM system, and no leaks were found during shutdown periods. This system was reproduced and tested at the Argonne National Laboratory Acoustic Leak Detection (ALD) Facility. The analysis of the results suggests that (a) leaks as small as 0.002 gal/min could be detected, (b) the acoustic background level is very low, and (c) the system has limited dynamic range, saturating at $\sim$0.006 gal/min.

A midwestern utility has been using AEMs on safety relief valves and now has installed a similar system on a main recirculation line (28-in.) elbow. High-temperature piezoelectric accelerometers are placed directly on the pipe (one on the top and one on the bottom). The system detects signals from leaks in the 20-50 kHz range and employs a spectrum analyzer to verify that a leak is present. (Signals in a specific frequency window suggest the presence of a leak.)

Numerous low-frequency AEM systems (with high-temperature accelerometers) have been employed since 1974 to monitor valves for leakage at one eastern reactor. The primary cause of plant shutdown has been valve packing gland leaks. Leaks as low as 0.5 gal/min can be detected.

3. EXPERIMENTS AT ARGONNE NATIONAL LABORATORY

Three IGSCC specimens, two thermal fatigue cracks (TFCs), and one mechanical fatigue crack (FC) have been installed in the ALD facility at Argonne National Laboratory [4,5]. Figure 2 shows acoustic leak data acquired from these six cracks. These data are normalized to a 375-kHz acoustic emission transducer (AET-375) on a waveguide, responding to a leak with a water temperature of 260°C (500°F) and pressure of 7.7 MPa (1100 psi). The largest correction (due to water temperature) is for the mechanical fatigue crack FC #1. Corrections for the other data are less than 3 dB. Transducer signals indicated in Fig. 3 are for a 300-400 kHz bandwidth and represent the signal after electronic noise levels are subtracted. The acoustic signals from the fatigue cracks vary approximately as $(\text{leak rate})^{0.7}$, whereas the signals from the IGSCCs vary approximately as $(\text{leak rate})^{0.32}$. Frequency analysis also indicates less dependence of acoustic signal on frequency for the IGSCC specimens than for the fatigue cracks (as well as for two valves and a flange that were also tested). An analysis of the frequency spectrum may provide information on the source of acoustic leak signals. The excellent matching of acoustic leak data in the 300-400 kHz range for the three IGSCC specimens, despite their different geometries, suggests that it may be possible to derive leak rate information from the amplitude of the acoustic leak signal in this frequency range.

Detection of a leak requires that $S_e = S_l - T - N + PG > 0$, where S_e = signal excess at detector output, S_l = source level (affected by waveguide geometry, insulation, and circumferential position), T = transmission loss down pipe, N = background noise level, and PG = system gain (all in dB). The acquisition of acoustic leak data, background noise estimates [4,5], and attenuation data allows a rough estimation of the sensitivity of an ALD system under field conditions. Figure 3 shows predicted signal-to-noise ratios (in dB) vs distance along a 10-in. Schedule 80 pipe for three leak rates and three levels of estimated acoustic background noise. The highest level is estimated from the maximum acoustic level obtained during the Watts Bar (PWR) hot functional test when the reactor was at operating temperature and pressure. The lowest level is obtained from an indirect estimate of background noise from Hatch (BWR) and the assumptions that the reactor acoustic background level will vary by a factor of 10 in the plant and that the measurement at Watts Bar was an upper-limit value. The striped area suggests possible enhancement of the acoustic signal for a 0.1-gal/min leak rate in a situation where the leak plume strikes the reflective insulation. Results of laboratory experiments suggest that for leak rates greater than 0.02 gal/min but less

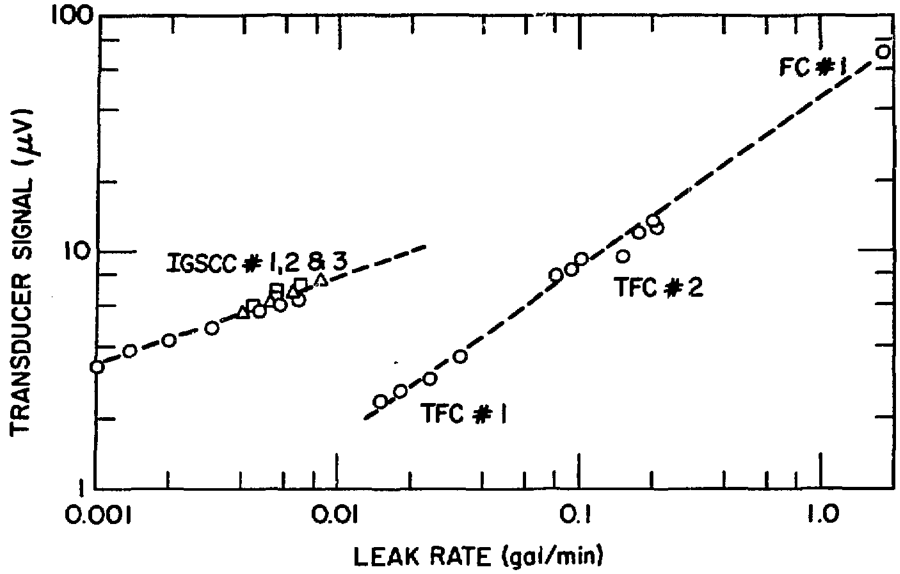

Figure 2. Acoustic Leak Data from Six Cracks Examined at Argonne National Laboratory. Data are normalized as described in the text. Signal amplitudes are for a 300-400 kHz bandwidth after electronic background noise is subtracted.

than 0.2 gal/min, signals could be enhanced significantly, given the correct circumstances. The following equation has been used to generate the curves of Fig. 3:

$$S = 20 \log_{10} \left(\frac{70\ R^{0.32}}{B}\right) - \begin{Bmatrix} 4.5D \text{ for } D < 2 \text{ m} \\ 5.6 + 1.7D \text{ for } D \geq 2 \text{ m} \end{Bmatrix} + \left\{ 6 \text{ if } 0.01 < R \leq 0.1 \right\}, \quad (1)$$

where S is the signal-to-noise ratio in dB, R is the leak rate in gal/min, B is the acoustic background level in μV (4, 20, or 40), and D is the distance from the leak in meters. Equation (1) assumes a signal loss of 4.5 dB per meter for the first 2 m, followed by a further loss of 1.7 dB/m. The acoustic signal is assumed to vary as (leak rate)$^{0.32}$. A 6-dB signal enhancement is added to the 0.1-gal/min curve to indicate how the presence of reflective insulation could improve the signal-to-noise ratio. For low acoustic background levels, a 1-gal/min leak would be detected at a distance of 11 m. With a high background level, this leak would be detected only at a distance of 1 m.

A laboratory test has been carried out to help evaluate the capability of a digital continuous acoustic monitoring system [4,5] to locate a leaking field-induced IGSCC by averaging cross-correlation functions. Two AET 375-kHz receivers were placed on waveguides; one 61 cm, the other 103 cm from IGSCC #1. A 0.003-gal/min leak was generated from IGSCC #1 at 504°F and 1000 psi. With the flow off and electronic filters passing 150- to 500-kHz signals, the electronic background noise levels were 31 and 42 mV. With the flow on, the signal amplitudes increased to 51 and 68 mV. The sampling rate for these tests was 500 kHz (2 μs between data points). Nine correlograms were averaged. In generating these correlograms, one of the two waveguides was moved circum-

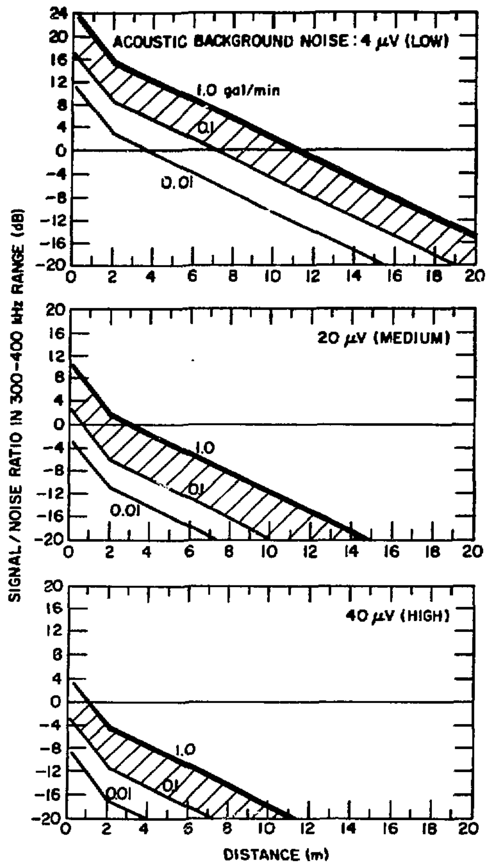

Figure 3. Predicted Acoustic Signal-to-Noise Ratios vs Distance along a 10-in. Schedule 80 Pipe for Three Leak Rates and Three Levels of Estimated Acoustic Background Noise. The striped areas indicate possible enhancement of the signal for the 0.1 gal/min leak because of the presence of reflective insulation.

ferentially (about 60°) before the next waveform was captured. This averaging technique permitted a leaking field-induced IGSCC to be located, for the first time, by cross-correlation techniques. The location accuracy of the system, however, has yet to be determined. Similar tests carried out with an electronic leak signal indicated that location accuracy improves with signal amplitude. This result suggests that larger leaks would be located with greater reliability. Only three different positions at each waveguide location were required to acquire the nine correlograms. Thus, the averaging procedure could be carried out with three transducer/waveguide systems at each monitoring site. It may be possible to carry out cross-correlation analysis with one transducer at each monitoring site, if larger leaks are present. Future tests will address this point.

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