Completed Research for Improved Codes and Standards on Steam Generator Tube Inspection and Plugging

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ABSTRACT

This paper discusses extensive research supported by the U.S. Nuclear Regulatory Commission (NRC) to develop information on the margin-to-failure of degraded steam generator tubing and the reliability and effectiveness of eddy-current (EC) in-service inspection techniques to detect and size degradation. Burst and leak-rate test results are described along with empirical models to correlate flaw geometry and size with remaining tube integrity. Results of round robin examinations to determine EC inspection reliability are presented. An evaluation and comparison of various sampling/inspection schemes for in-service inspection of steam generators is discussed.

1. INTRODUCTION

In 1976, the NRC initiated the Steam Generator Tube Integrity Program (SGTIP) in response to an Atomic Safety and Licensing Board inquiry regarding the existence of NRC data on the integrity of service-degraded steam generator tubes. At that time the available data were limited in quantity and had been generated solely by steam generator vendors. The Pacific Northwest Laboratory was authorized by NRC to conduct a three-phase program to develop the needed tube integrity and EC reliability information. Phase I consisted of burst and collapse tests, and single-frequency EC examinations of tube segments with machined flaws that simulated known or postulated service-induced degradation. In Phase II, a smaller number of the same flaw types were investigated, but specimens were flawed by chemical means rather than precision machining methods. The third phase of the program utilized a retired-from-service steam generator as a source of service-degraded tubing to further validate the tube integrity constitutive equations and to develop information on the reliability of conventional EC and alternative field practice inspection techniques to detect and size flaws under simulated service conditions. This paper highlights significant results from more than eleven years of research on steam generator tube integrity and nondestructive evaluation (NDE) issues. The information from this program is being used by NRC to update the regulatory guides governing steam generator in-service inspection and tube plugging criteria.

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2. MECHANICAL INTEGRITY TESTS

2.1 Tube Integrity Constitutive Equations

A main objective of the SGTIP was to establish validated models, based on experimental data, for predicting the margin-to-failure of service-degraded tubing under normal operating and accident-loading conditions. To reach this objective, specimens of Inconel 600 steam generator tubing manufactured to 1977 practice were mechanically flawed to simulate known or postulated defects present in steam generators. These specimens were then burst and collapse tested at steam generator operating temperatures under controlled loading conditions. All sizes of Inconel 600 tubing used in the United States were tested, as well as three different strength levels of a single tubing size. In all, more than 600 specimens were tested. From the data, constitutive equations were developed relating remaining tube strength to flaw size and geometry. The equations developed for burst loading conditions were the following:

For electro-discharge machined (EDM) slots

$$\Delta P/\Delta Po = 1 - (h/t) + (h/t) \exp\{-0.373 L/\sqrt{Rt}\}$$

For uniform thinning

$$\Delta P/\Delta Po = (1 - h/t) \{1 - \exp[-0.13 L/\sqrt{R(t - h)}]\}$$

For elliptical wastage

$$\Delta P/\Delta Po = (1 - h/t)^{0.604}$$

where

$\Delta P/\Delta Po$ = defected to undefected burst pressure
h = defect depth
t = wall thickness
R = inner radius of tube
L = defect length.

The constitutive equations were validated by testing tube specimens with artificial flaws created by chemical means and by testing service-degraded tubes taken from the retired-from-service steam generator. Figure 1 shows a comparison between predicted, normalized burst strength and measured values for service-degraded tube specimens. The EDM slot equation was used to calculate expected burst pressures. Note predicted results are within ±10% of measured values except for one data point.

2.2 Leak-Rate Calculations and Comparison to Experiment

The objective of this work was to determine if a stress corrosion crack (SCC) will leak at a rate that is consistent with the length of crack and the fluid pressure differential across the tube wall. The accuracy of leak-rate predictions is an important consideration in evaluation of leak detection limits as they relate to allowable leak rates given in plant technical specifications.

Three sets of experimental data were used in the evaluation: data from Powell and Hall (1987), Berge (1987), and data produced by Battelle-Columbus Laboratories under subcontract to the SGTIP. A simple predictive model was developed to aid in interpretation and comparison of the data. This model was adapted from one developed for leakage from axial cracks in reactor pressure vessels (Simonen et al., 1986). The model used fracture mechanics concepts to predict crack opening area as a function of length and pressure differential across the tube wall. Given this crack opening area, well-known equations from the fluid mechanics literature for flow through an elongated orifice were then used to predict leak rates.

Figure 2 shows a plot of typical leak rate data (Powell and Hall, 1987) at normal reactor operating conditions as a function of axial crack length. Curves giving predicted leak rates are also plotted for comparison with the experimental data. Crack lengths were reported as bounding values: in Figure 2, the average crack length was plotted. The data show a large degree of uncertainty in expected leak rates. Some reasons for the unpredictability of leak rates may be 1) small crack openings that could be plugged by impurities in the water, 2) residual stresses from fabrication and precracking of the tube, which could cause either crack opening or closure, 3) crack roughness, which can only be approximately estimated and is subject to considerable variation, and 4) the lengths of the cracks, which were reported with a wide range and no doubt differed from the ideal through-wall cracks used in the model.

The main conclusion of the evaluation was that actual leak rates as measured during tests can be highly variable. These leak rates can be strongly influenced by "random" variables that are not addressed in the predictive models that have formed the basis for establishing leak detection limits. Measured leak rates are often up to a factor of ten less than predicted rates. This suggests that a substantial level of conservatism should be applied to predictions of leakage used to establish detection limits for plant leak detection systems.

3. EDDY-CURRENT INSPECTION RELIABILITY

3.1 Steam Generator Group Project

Information on the reliability of EC inspection techniques to detect and size flaws in laboratory and service-degraded tubes was developed throughout all phases of the SGTIP. The most extensive and realistic data base was obtained from round robin examinations of the retired-from-service Surry 2A steam generator.

A subset of 320 tubes was selected from the 3388 tubes in the generator for round robin examination. Results from two multi-frequency base-line EC inspections of the generator were used to establish its post-service condition and provide a basis for selecting round robin tubes. In addition, the in-service history of the generator and visual inspections of the secondary side were also used to supplement the base-line inspection data.

Four round robins were then performed to determine the reliability of conventional multi-frequency EC inspections and alternative NDE methods. To validate the in situ NDE results, more than 550 tube segments were removed from the generator. Pitting and wastage were the predominant tube defects found. The most severe pitting/wastage degradation was located in the region 0 to 2 in. above the hot leg top of tube sheet (TTS) where wall losses ranged up to 87%. Wide variations in the distribution and depth of degraded areas were observed both axially and circumferentially within the corroded region of the hot leg TTS specimens. These variations in defect distributions appear to be a major factor in the variability of the EC depth estimates. In general, wall loss from pitting/wastage-type degradation in specimens from other regions of the generator was less than 20%.

Estimates of the probability of detection (POD) were obtained by matching the EC inspection results with data from both visual and destructive metallographic analysis of the removed specimens. For each "true flaw size" category, the number of nonzero EC indications divided by the total number of flaws in that size category was used as a POD estimate. Results of these analyses indicated that POD depended on flaw severity. For pitting/wastage type flaws, the POD increased with wall loss and approached 0.9 for flaws greater than 40% through-wall. Insufficient numbers of other defect types at other locations where EC inspections were made precluded additional POD evaluations.

Figure 3 is a plot of the POD estimates for seven teams employing conventional multi-frequency EC inspection techniques. The data in Figure 3 were based on metallographic determination of wall loss. The curve in Figure 3 is an approximate 90/90 lower tolerance limit (LTL) for individual team performance over the population of teams from which the seven teams plotted are assumed to be a sample. That is, if each team in this overall population had inspected this same set of tubes, we can be approximately 90% confident that 90% of the teams in the population would have produced estimated POD values greater than the LTL. Note that the part of the curve that extends from about 65% to 85% wall loss is flat because the number of specimens with defects in this range is inadequate to provide a meaningful estimate of the LTL. Thus, the LTL at 65% wall loss was extended as a conservative approximation of the LTL for wall loss $\geq$65%.

Wide variations in the reported EC depth estimates were observed between specimens with similar wall loss and also within the same specimen for data from different inspection teams. The team-to-team variations for a given specimen appear to result from differences in analysis procedures or the analyst's interpretation of the complex EC patterns. Defect morphology and distribution within the corroded region were considered the major cause for variations between specimens with similar wall loss. However, dents and deposits near the defects also contributed to the sizing variations. In general, teams tended to undersize pitting/wastage type degradation, especially for severely degraded specimens. Figure 4 shows the relationship between EC estimated defect depth and metallographic results for a typical inspection team using conventional inspection techniques. A better correlation was observed for one team using alternative inspection techniques, as shown in Figure 5.

3.2 SCC Mini Round Robin

To supplement the EC reliability information obtained from the round robins on the steam generator, an additional round robin was performed to provide information on the reliability of EC techniques to detect and size SCC. A tube bundle including tubes with laboratory-produced SCC of varying part-through-wall depths and lengths was assembled and sent to several firms that routinely conduct in-service inspection of steam generators. Some of the tubes were coated with a 1- to 2-mil nonuniform layer of copper to simulate the deposits found on tubes removed from the retired-from-service steam generator.

Each round robin participant performed a standard bobbin-coil inspection with 100 kHz and 400 kHz frequencies and any other frequencies of their choice. Each was also asked to inspect the tube bundle with any alternative technique desired. Typically, specially designed bobbin-coil and rotating pancake-coil probes were used for the alternative inspections.

Results indicated that the average POD of SCC by conventional bobbin-coil and alternative inspection techniques was low. The average POD for teams using conventional inspection techniques was 0.5. For teams using rotating pancake or array coil techniques, the average POD was slightly higher at 0.63. The reliability of the various EC techniques to determine SCC length and depth was neither accurate nor precise. The alternative inspection results did not show improved sizing capability compared to conventional bobbin-coil techniques.

4. EVALUATION OF SAMPLING PLANS FOR IN-SERVICE INSPECTION

The objective of this work was to evaluate and compare a limited number of candidate sampling/inspection schemes for in-service inspection of steam generator tubes. A primary criterion for comparing sampling/inspection schemes is the probability of detecting and either plugging or repairing a tube that has a flaw with a specified size. For a single tube, this probability is a function of two other probabilities: 1) the POD, which is the probability of observing an EC reading from a degraded tube; and 2) the conditional probability, denoted by PEL, that the EC reading will exceed the plugging limit and result in plugging or repairing the tube. Both the POD and PEL are functions of the true size and type of flaw. They also depend upon the capability and reliability of the inspectors and their equipment.

The EC reliability data from the retired-from-service generator were used to develop empirical models of POD and PEL as functions of true flaw size for tubes with pitting/wastage type flaws. Because multiple inspection teams were involved, the statistical modeling yielded a range of estimated POD and PEL values for each specified flaw size. These ranges of values were utilized with probability theory and Monte Carlo simulation techniques to evaluate and compare candidate sampling/inspection schemes.

In the analytical evaluation of the sampling/inspection schemes, it was assumed that defective tubes (in this study tubes with flaws $\geq$ 75% through-wall) tend to occur in clusters of degraded and defective tubes. For this analysis, a cluster configuration consisting of one defective tube surrounded by four degraded but not defective tubes was assumed. This cluster configuration was chosen because it would be harder to detect than a larger cluster or a cluster that includes more than one defective tube; it should, therefore, provide conservative (lower bound) results. Of course, in an actual generator, a cluster could have a different shape and composition than were assumed for this analysis.

Two systematic/sequential sampling schemes were evaluated in this study. In these sampling schemes an initial systematic sample of either 20% or 40% of the tubes was selected and each tube was inspected. When an EC indication due to degradation was observed, inspection continued in the region immediately surrounding the suspect tube until a 2-tube "buffer zone" consisting of tubes with no EC indications was observed. Each tube with an EC indication exceeding the plugging limit was plugged or repaired. As a basis for comparison, 100% inspection was evaluated; however, the analytical results for 100% inspection did not depend on the clustering assumption.

Results of the analytical evaluation indicated that even with 100% inspection, most teams that inspected the retired-from-service generator cannot detect and plug more than 65% of the defective tubes present. Analysis of sampling/inspection schemes demonstrated that if the clustering assumption holds, and if the POD for the degraded tubes in the cluster was at least 0.7, then 40% systematic sequential sampling was nearly as effective as 100% inspection for detecting and plugging defective tubes. This was true for any PEL value. However, 20% systematic sequential sampling was found to be significantly inferior to both 100% inspection and the 40% systematic scheme. Figure 6 illustrates these results by plotting the joint probability of detecting and plugging a defective tube against the PEL.

A Monte Carlo simulation analysis was conducted to further evaluate and compare the effectiveness of the 20% and 40% systematic sequential sampling/inspection schemes. Tube maps representing seven different distributions of degraded and defective tubes were considered. Six POD models, two EC sizing models, two plugging limits, and the effect of false calls were considered in various combinations with the tube maps. At each combination of these "input parameters," repeated application of 20%, 40%, and 100% inspection were simulated. Summary results were then tabulated for comparison.

The results of the Monte Carlo simulations support the conclusions reached from the analytical evaluation and provide additional insights. When the clustering assumption held, 40% systematic sampling tended to be nearly as effective as 100% inspection, but required substantially less inspection. However, when the clustering assumption did not hold, 40% systematic sampling was not as close to 100% inspection, but was better than the 20% systematic sampling plan. When the defective tubes were in one large cluster with degraded tubes, all three sampling/inspection schemes were equally effective. Improving the POD and flaw sizing capability to the best observed in the NDE round robins on the steam generator yielded improved effectiveness of all three sampling/inspection schemes. Simulations performed with a 0.05 false-call probability indicated that the number of tubes inspected over the initial sample increased by 19% to 26%. However, a 0.05 false-call probability did not cause either the 20% or 40% sampling scheme to increase to 100% inspection.

5. REGULATORY APPLICATION OF RESEARCH RESULTS

The research results from the SGTIP are being used by the NRC to update Regulatory Guides 1.83 and 1.121 covering steam generator in-service inspection and tube plugging criteria. The revised guides will include improved requirements for EC inspection equipment and procedures. The sampling plan in Regulatory Guide 1.83 is also being revised as the result of the statistical evaluations described above. The extensive tube integrity data base is being used to develop improved methods for determining tube plugging limits.

In addition, the SGTIP has pursued adoption of improved EC inspection methods by the ASME Code. The SGTIP has been involved with the Section XI Special Working Group on EC Examination to transfer research results and provide technical input for revision of Appendix IV.

6. REFERENCES

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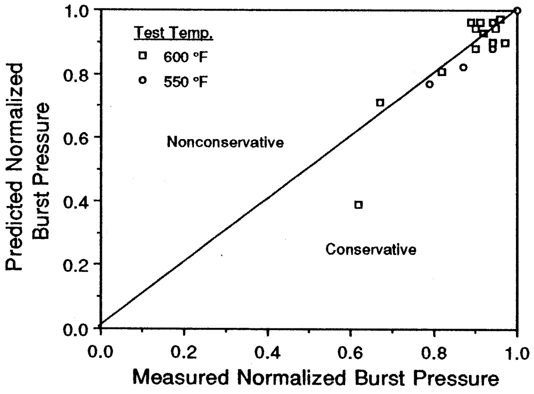

FIGURE 1. Comparison of Predicted and Measured Normalized Burst Pressure for Service-Degraded Steam Generator Tubes

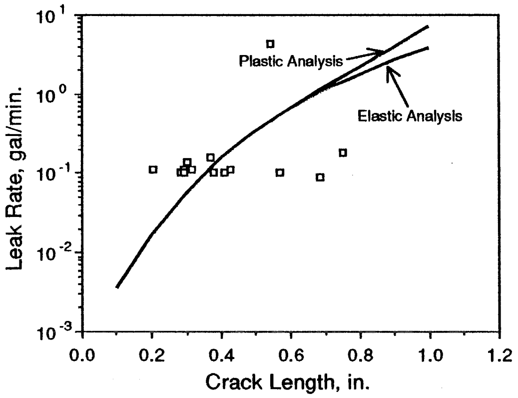

FIGURE 2. Comparison of Powell and Hall Leak Test Data with Model Predictions, Normal Operating Condition

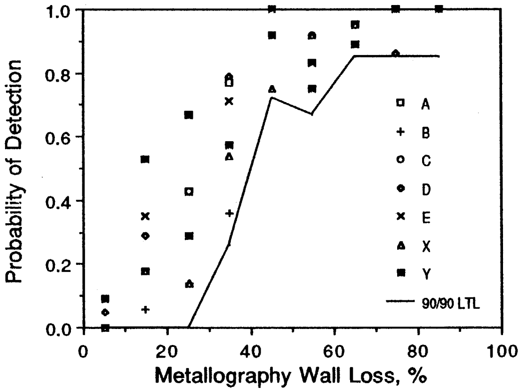

FIGURE 3. Individual POD Values and 90/90 LTL for Teams Using Conventional Multi-Frequency EC Inspection Practice

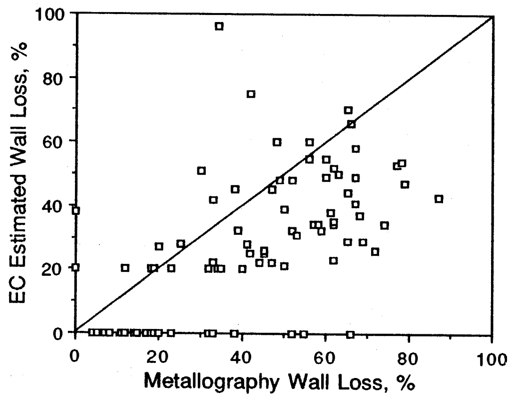

FIGURE 4. Typical Plot of EC Estimated Flaw Depth Versus Actual Depth from Metallographic Analysis

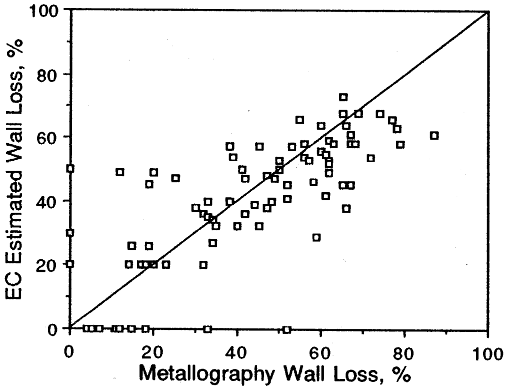

FIGURE 5. Plot of Best Observed EC Estimated Flaw Depth Versus Actual Depth from Metallographic Analysis

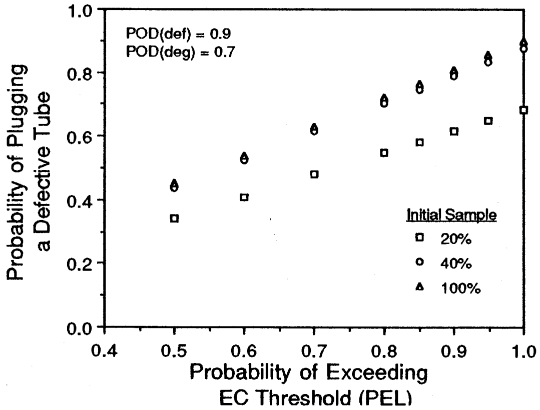

FIGURE 6. Probability of Plugging a Defective Tube Versus the Probability of Exceeding EC Threshold (40%) for Various Initial Sample Sizes