Qualification of eddy current techniques and personnel for inspection of steam generator tubes

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ABSTRACT: A committee of US. and international experts on inspection of nuclear steam generator tubes has developed guidelines for performance demonstration of eddy current examination techniques and qualification of NDE personnel for analysis of eddy current data. Implementation capabilities for data analyst qualification have been incorporated in an interactive software shell that handles training material, database, tests and their automatic grading, and record keeping. This paper describes the program elements and presents some of the implementation results of the last two years.

1 INTRODUCTION

Reliability of eddy current inspection techniques and the ability of NDE personnel for analysis of eddy current signals from nuclear steam generator tubes have been questioned by utilities and regulators. Their concerns stems from the number of missed indications and leakage-forced outages that have occurred in the last few years. With aging plants and steam generators that have experienced several forms of tube degradation, plant operators find themselves in the position of having to rely more and more on in-service inspections (ISI) as a vital element of their overall steam generator management strategy. To address these concerns, EPRI organized a group of eddy current experts to develop performance demonstration guidelines for qualification of eddy current techniques and personnel who perform signal analysis.

These guidelines designed for in-house implementation by utilities and inspection organizations, are described in Appendices G and H to the PWR Steam Generator Examination Guidelines (EPRI report NP-6201, Revision 3, November 1992, often referred to as the ISI Guidelines). The EPRI NDE Center, following these guidelines, has developed an implementation package containing training and testing materials for personnel qualification. This implementation package is in the form of a database that can be accessed through an interactive software shell. Qualification candidates, under supervision of a proctor, can access the program from a computer terminal and go through its various stages of training/review, written test, and practical test. Selection of test questions and grading of tests are done automatically and are under secured software control to ensure uniform implementation at different organizations. It typically requires two weeks to complete the program. The first week is spent in...
reviewing steam generator designs, defect types and histories along with eddy current techniques and analysis methods. The second week is devoted to the practical test where some 5000 eddy current signals that include those from thinning, pitting, wear, primary water stress corrosion cracking (PWSCC), intergranular attack (IGA), secondary side stress corrosion cracking (ODSCC), and impingement are analyzed by each candidate.

The industry-wide personnel qualification program provides the assurance that each analyst possesses the necessary general knowledge and skill levels. To address individual utility's need for analysts with plant-specific knowledge and skills, EPRI has developed a site-specific version of the performance demonstration program that provides flexibility for each plant to devise a program with defect, data, and grading schemes of interest to them.

Development of these programs, their assessments and implementations have all been under the guidance of industry representatives and continue to receive expert peer reviews as additional techniques and data are qualified for inclusion in the database. The implementation package for the industry-wide performance demonstration, in the form of optical disks, has been available to the US and international members of the EPRI's Steam Generator Strategic Management Project since mid-1993.

As of early 1995 more than 225 data analysts have successfully completed the qualification program. Implementation package for the site-specific performance demonstration has been available since late 1994.

2. PROGRAM ELEMENTS

Details of the US program for qualification of eddy current techniques and personnel are given in Appendices G and H of EPRI's Steam Generator ISI Guidelines. Some important elements of the program are described below.

2.1 Test samples

One of the major obstacles in conducting a reliable performance demonstration or a round robin on inspection of flaws in nuclear plant components is the availability of sufficient types and number of samples that adequately and realistically represent the field situation. In the case of steam generator tubes, the ideal situation would be to collect field data and pull tubes for metallographic verification. This is the most reliable approach, however, because tube pulls are expensive and infrequent, they seldom provide the necessary quantity and variety of data. It is possible to fabricate flawed tubes in test boilers that simulate field environment, but the quality of samples in terms of the fidelity with which they represent real field defects have not always been acceptable and the cost is usually prohibitive for a large number and variety of samples. While the use of physical test samples or pulled tubes are essential for technique qualifications, one alternative for qualifying analysts has been the use of field collected ISI data to be used as test samples. This not only has the advantage of being collected from real flaws, but it also affords a large amount of data from many plants and degradation forms. The disadvantage of field data is that its ground truth has not been established in any definitive way, except in those cases where tubes have been pulled and metallographically examined.
Considering all factors, the US program for qualification of analysts has elected to use field data and establish ground truth by the so-called "expert opinion". The rationale for this approach has been that the field data that is typically analyzed by two analysts, a primary and a secondary analyst in the field, is subjected to a peer review by a group of expert analysts. The peer review is conducted in a group setting where expert analysts share and apply their collective wealth of experience along with other available data, such as relevant pulled tube information, to the analysis of the field data. The field data that has been peer reviewed then goes into the database for use in testing analysts. The initially selected data set whose ground truth has been verified and established by the peer review gets additional scrutiny after being used in several performance demonstration examinations. Periodically, the test results are reviewed to identify those signals that have been called by the students which were not considered flaws by the "experts" in the original test set, as well as those flaw signals that are not called (missed) by majority of the candidates -- indicating that the "experts view" of them as flaws may be in question. This type of added scrutiny and post-analysis enhances the test reliability. Thus, it has been performed several times during the last two years and each time has resulted in the adjustment to the ground truth by inclusion of some and deletion of other signals to the test sets.

While no claim is made as to the infallibility of this sample selection process, we have found that considering all limitations and constraints that exist in the establishment of realistic test sets, our approach continues to be a good compromise in providing the largest amount of realistic data that covers many plants, steam generator models, and flaw types.

2.2 Qualification of techniques

Eddy current techniques are qualified per Appendix H of the ISI Guidelines. All technique qualifications are conducted on real physical samples that have known ground truth, or pulled tube data where both eddy current signals and metallographic results are available. The sample set for technique qualification must be such that at least 2/3 of its flaws are ≥60% through wall (TW). Acceptance criteria for technique qualification are described below.

Acceptance criteria for detection is 80% probability of detection (POD) for flaws 20-59% TW, and 80% POD at 90% Confidence Level (CL) for flaws ≥ 60% TW. The through-wall dimensions are actual metallographic dimensions and the 60% TW is selected to be on the conservative side of the estimated critical flaw size.

Acceptance criteria for depth sizing is ≤25% root-mean-squared error (RMSE) for a qualified detection set. A qualified detection set for depth sizing qualification is a set of flaws that meet the detection criteria described above.

As of this writing there is no acceptance criteria for length sizing. Efforts are underway to develop such a criteria for length sizing of stress corrosion cracks on the primary (inside surface) and secondary (outside surface) of the steam generator tube.

Figure 1 shows an example of technique qualification for detection. It specifically shows that the prime/quarter differential mix bobbin technique is qualified for detection of ODSCC per acceptance criteria described above. Figure 2 shows an example of a qualified technique for depth sizing of wear.
Figure 1. Example of technique qualification for detection. Number of samples used and detected in each of four through-wall depth categories are shown as fractions on top of bars. This technique shows acceptable performance per Appendix H.

Figure 2. Example of technique qualification for depth sizing. Technique shown is an acceptable technique for depth sizing of wear defects per Appendix H.
2.3 Qualification of Personnel

Eddy current analysts are qualified per Appendix G of the ISI Guidelines. The sample sets used for testing analysts are real field collected data whose ground truth has been verified and established by expert opinion as described before. All analysis techniques used in the personnel qualification tests must be qualified techniques in accordance with Appendix H. Candidates are expected to first pass a written exam before being allowed to proceed with the practical examination. Practical examinations are given in the areas of thinning, pitting, wear, primary water stress corrosion cracking (PWSCC), intergranular attack (IGA), secondary side stress corrosion cracking (ODSCC), and impingement.

For each damage mechanism, the acceptable performance criteria for detection is 80% POD at 90% CL for defects that are \( \geq 40\% \) TW for bobbin and rotating pancake coil probes. For defects < 40% TW, 80% must be detected. There is a limit of 10% on overcalls that must not be exceeded. For depth sizing of flaws, where qualified techniques exist, the performance criteria limits the sizing error to \( \leq 10\% \) RMSE for the entire range of flaw depths.

If a candidate fails to achieve a passing score on any of the damage mechanisms in the practical examination, he or she will be allowed to re-take that part of the examination after a review of the indications that he or she missed. Upon failing the first re-test, the candidate must receive a minimum of 8 hours of additional training prior to taking a second re-test. Upon failing a second re-test, the candidate must receive a minimum of 40 hours of training, wait at least 30 days, and start at the beginning and take the complete set of written and practical examinations in the same manner as any first time candidate.

2.4 Re-qualification

Re-qualification of analysts is similar to ASME where Level IIIs are required to re-qualify every 5 years and Level IIs are required to re-qualify every 3 years. Tests for re-qualification are based on a reduced data set and passing is based on the accumulative grade for the whole test as opposed to a passing grade on each separate degradation mechanisms. Failing a re-qualification test requires re-taking of the complete qualification examination similar to a first time candidate.

3. PROGRAM IMPLEMENTATION

Upon completion of the program development in the late 1992 and prior to its widespread distribution, 31 analysts from US utilities and inspection vendors participated in a trial implementation (dry run) of the software shell and its database of training and test material at the EPRI NDE Center. 20 of the 31 participants were able to successfully complete the qualification tests. As the result of this trial implementation the program has been further refined by addition of data where data was insufficient, and modification of test questions to enhance clarity and relevance. Currently more than 20 organizations consisting of utilities and inspection vendors from the US and abroad are implementing the program at their respective locations where more than 225 eddy current analysts have successfully completed the program. Implementation results
are periodically fed back to the EPRI NDE Center where they are compiled and analyzed to identify those areas that are in need of revision and or improvement.

Figure 3 shows the average performance of the original 31 analysts who participated in the trial run of qualification exams for detection of different degradation modes in steam generator tubes. These results represent everyone's first attempt at the practical exam. As was mentioned above only 20 of this group of 31 were able to successfully complete the qualification exam. Only 2 analysts passed all of the practical exams the first time, the other 18 had to take some parts of the practical exam for a second time.

**Means and 90% Confidence Limits for Detection Performance**

![Bar chart showing percentage of indications correctly reported for different indication categories.]

Figure 3. Combined performance of the 31 analysts who participated in the trial implementation of personnel qualification program. Figure shows the mean and the 90% confidence limits for bobbin coil and MRPC detection of different defect types.

Qualitative observation of these results indicate that analysts as a group have a better performance on detection of degradation modes with which the industry has had the longest experience such as wear and thinning. This is not to say that a class of defects cannot be more difficult than other to detect, or that there are no differences in the performance of individual analysts.

Figure 4 shows results from the industry-wide implementation of the program where the combined performance of 134 analysts on bobbin coil detection of ODSCC is presented. This figure shows the probability of detection of ODSCCs of different eddy current signal voltages. Presentation of the probability of detection of ODSCC relative
to signal voltage is an important consideration in the disposition of tube defects because under special circumstances, steam generator tubes with low voltage ODSCCs may be kept in service. As more analysts complete the qualification requirements under this program, it is significant to note that combined performance of this group of 134 analysts on bobbin coil detection of ODSCC compares well to the combined ODSCC detection performance of the original group of 31 as shown in Figure 3.

**ODSCC/BOBBIN DETECTION RELATIVE TO SIGNAL VOLTAGE**

*Average Probability of Detection (PoD)*

*90% Lower-Bound Confidence Level for Average PoD*

<table>
<thead>
<tr>
<th>Voltage</th>
<th>PoD</th>
<th>90% CI</th>
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<tbody>
<tr>
<td>1.50 &amp; Above</td>
<td>0.952</td>
<td>0.939</td>
</tr>
<tr>
<td>1.00–1.49</td>
<td>0.934</td>
<td>0.915</td>
</tr>
<tr>
<td>0.50–0.99</td>
<td>0.870</td>
<td>0.852</td>
</tr>
<tr>
<td>0.00–0.49</td>
<td>0.729</td>
<td>0.702</td>
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Figure 4. Combined performance of 134 analysts on the bobbin coil detection of ODSCC relative to four separate signal voltage categories.

4. SITE-SPECIFIC PERFORMANCE DEMONSTRATION

Once an analyst successfully demonstrates a general level of knowledge and analysis skills through the industry-wide performance demonstration program on various steam generator models, degradation mechanisms, and analysis techniques, he or she may have to still pass a site-specific performance demonstration to satisfy a particular plant's needs and requirements. Individual plants often need to ensure that analysts are adequately trained and qualified in inspection areas of particular interest to them. These areas include steam generator makes and models, active and suspected degradation mechanisms, and analysis techniques that are specific to each plant.

EPRI has developed a site-specific performance demonstration program that is an extension of the general industry-wide performance demonstration program which allows each utility to tailor the program to their specific needs. The software shell is
designed to provide maximum flexibility to allow the program administrator on site to devise specific tests and grading criteria that best suits the plant's particular needs. While the system makes up a random test from the database and within the prescribed parameters, the site administrator has the ability to select or de-select any one or more tubes for a given test. In a typical implementation, the site administrator enters raw data and its answers and then determines the grading scheme, selection of tubes for each candidate, site, and degradation forms. The software will automatically grade the examination based on the truth input by the program administrator and provide time-dated reports.

4.1 Implementation

Recently a trial implementation (dry run) of the site-specific program was conducted to assess the overall performance of analysts on detection of bobbin coil voltages from ODSCC. The data set used in this study was the actual data collected from the field and consisted of 818 tubes, 49 of which contained no reportable indications. These tubes contained a total of 5726 tube support locations, each of which could potentially have a reportable indication. This means that each analyst in analyzing the data from these 818 tubes, would have to analyze a total of 5726 tube support plate locations. The study looked at three categories of indications:

1. Confirmed -- indications that were reported by field analysis and were also confirmed by motorized rotating pancake coil (MRPC) analysis (N=890).
2. Not Confirmed -- indications that were reported by field analysis but not confirmed by MRPC analysis (N=222)
3. Not Reported -- indications that were not reported by field analysis and were not subject to MRPC analysis, but (as a result of being reported by one or more analysts during this study) were then identified as reportable indications by peer review (N=251)

The above three categories provided a total of 1363 indications of varying bobbin coil voltages for this study. Bobbin coil voltages were categorized in seven different voltage bands from < 0.25 volt to ≥2.0 volts.

Analysis were completed of all tubes by a total of 12 Qualified Data Analysts who participated in this study. Analysis procedures used in this study were equivalent of those used in the field. Additionally the analysis data from the primary and secondary field analysis were also included as if they were equivalent of two additional analysts giving a total of 14 analysts. It should be noted that in the field the total number of tubes were analyzed by several analysts, but a given tube was analyzed by only two analysts, namely a primary and a secondary analyst. For this study, the results of all primary field analysts were treated as if they were done by one analyst, and the same was done for secondary analysts.

Average PODs and associated 90% lower-bound confidence levels were calculated for "confirmed" indications at each of seven voltage categories, for the samples of "not confirmed" and "not-reported" indications, and for all indications combined. Figure 5 shows the average POD and 90% lower-bound confidence levels of the 14 data analysts for confirmed indications at each signal voltage category.

Figure 6 shows the average POD and 90% lower-bound confidence level of 14 analysts for all 1363 indications combined (confirmed, not confirmed, and not reported).
Figure 5. Average PODs and 90% confidence levels for confirmed indications.

Figure 6. Average PODs and 90% confidence level for all indications combined.
This study provided the opportunity to compare the results of analysts participating in this trial implementation and special study to those working under field conditions. An understandable concern with data obtained by means of a special study is that the conditions of such a study do not duplicate field conditions and that, as a consequence, study results overestimate the PODs that would be obtained under field conditions. This analysis showed that the performance of study analysts correlated highly with field analysts. The average PODs for the sample of 12 study analysts were compared with the average PODs for the 2 (primary-secondary) field analysts. Comparisons were made by correlating the PODs of study and field analysts over the nine indication categories (7 voltage categories for confirmed indications plus the not-confirmed and not-reported indications). Figure 7 shows the correlation between PODs for the study and the field analysts.

![Correlation Diagram](image)

Figure 7. Correlation between PODs for study and field analysts. All not-confirmed and not-reported indications have been combined into their respective single category without regard to their voltages.

As expected, a high correlation was also observed between PODs and overcalls. Analysts with higher PODs tended to also have the larger numbers of overcalls. Figure 8 shows how the overall POD for each of the 14 analysts compares with their respective number of overcalls.
5. SUMMARY

The US program for qualification of eddy current techniques and analysts for inspection of nuclear steam generator tubes was developed in 1992 by a committee of US and international experts and since then has seen wide spread implementation. To date more than 225 analysts have successfully completed the program requirements. A site-specific version of this performance demonstration program was developed in 1994 and it has completed its trial implementation. Prominent features of these programs are their ease of implementation afforded by the interactive software shells that run the programs. These programs have been used to assess and qualify performance of individual analysts as well as to document overall capabilities for inspection of specific degradation mechanisms in steam generator tubes. Where needed, programs offer security of the test data and records plus the flexibility of tailoring features to site-specific requirements. The industry-wide and the site-specific versions of performance demonstration program are available to the US and international members of the EPRI's Steam Generator Strategic Management Project.