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ROLE OF NDE IN INTEGRITY ASSESSMENT OF STEAM GENERATOR TUBES

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ABSTRACT

Nuclear steam generator condition, in terms of structural and leakage integrity, is determined by the type and number of defects present in the steam generator. Periodic evaluation of steam generator tube integrity in US PWR plants is governed by the Nuclear Energy Institute (NEI) Initiative 97-06. This evaluation takes place at each refueling outage and its aim is to ensure that the steam generator performance criteria are met. The two elements of this evaluation, at each refueling outage, are condition monitoring and operational assessment. Condition monitoring is a backward look in time to establish that performance criteria were not violated during the previous operating cycle. This is typically done via NDE techniques to find if the tubes contain any defects exceeding structural limit. Operational assessment is a forward look in time to determine that the steam generator tubes can operate another cycle without violating performance criteria, and that also uses NDE data as input to establish beginning of cycle and end of cycle conditions. Requirements for steam generator integrity assessments dictate the particular inspections that must be conducted and the NDE data that needs to be generated. This data ranges from identification of various degradation forms, probability of detection (POD) statistics, flaw sizing measurements, and NDE variability and uncertainties associated with techniques, analysts, and the overall inspection system. Additionally, were possible, the degrading effects of material noise on POD and sizing capabilities should quantitatively be considered.

INTRODUCTION

Integrity assessment of the many thousands of steam generator tubes in a PWR plant involves a determination of their potential degradation during operation, leading to a series of decisions as to run, repair, or remove any given tube from service. In other words, each tube must satisfy a certain performance criteria during the operation, and if it does not, remedial action must be taken. The role of NDE in the integrity assessment of steam generator tubes is to give input to this process and facilitate the run/repair/retire decisions. Periodic evaluation of steam generator tube integrity in US PWR plants is governed by the Nuclear Energy Institute (NEI) Initiative 97-06, [1]. This evaluation takes place at each refueling outage and its aim is to ensure that the steam generator performance criteria are met. The two elements of this evaluation, at each refueling outage, are condition monitoring and operational assessment. Condition monitoring is a backward look in time to establish that performance criteria were not violated during the previous operating cycle. This is typically done via NDE techniques to find if the tubes contain any defects exceeding structural limit. Operational assessment is a forward look in time to determine that the steam generator tubes can operate another cycle without violating performance criteria, and that also uses NDE data as input to establish beginning of cycle and end of cycle conditions. Requirements and guidance for steam generator integrity assessments [2] dictate the particular inspections that must be conducted and the NDE data that needs to be generated [3]. This data ranges from identification of various degradation forms, probability of detection (POD) statistics, flaw sizing measurements, and NDE uncertainties associated with techniques, analysts, and the overall inspection system.

An important element of the inspection process that is often not adequately addressed, is the effect of noise on POD and sizing capabilities. Material noise at flaw location can degrade the inspection system's POD and in the extreme can mask the flaw and prohibit its detection. In its ongoing efforts to develop tools for integrity assessment of steam generator tubes, EPRI is conducting an extensive study to develop noise-adjusted POD and sizing capabilities to enhance the value of NDE input to SG integrity assessments.

Performance Requirements

The performance criteria that steam generator tubes must satisfy during their operation are based on structural tube integrity, postulated accident leakage, and operational leakage. In general terms, they are:

- Steam generator shall retain structural integrity over the full range of normal operating conditions and design basis accidents. This includes retaining a margin of 3 against burst under normal operation and a margin of 1.4 against burst under design basis accident.
- The accident-induced primary to secondary leakage rate is not to exceed 1 gallon/minute per steam generator.
- The operational leakage from primary to secondary is not to exceed 150 gallon/day from any one steam generator

Total primary to secondary accident leakage for each degradation mechanism shall account for the inspection sample size, POD and how POD may be affected by noise that can reduce detection capability.

Elements of Integrity Assessment

Assessment of steam generator tube integrity involves two critical elements, which are referred to as condition monitoring and operational assessment. Additionally, there is another important step that takes place as part of outage preparation, called degradation assessment.

Degradation assessment is a pre-planning step before the outage through which the condition of the steam generator must be determined in terms of existing degradation as well as potential for development of new degradation types. Degradation assessment leads to the selection of the necessary inspection techniques as well as determination of sampling strategies for the planned inspection campaign.

Condition monitoring is a process of looking backward in time to confirm that adequate steam generator tube integrity has been maintained during the previous operating period. It involves a nondestructive evaluation of the as found condition of the tubing relative to integrity performance criteria. It looks for the onset of new degradations as well as growth of existing ones.

Operational assessment is the process of looking forward in time to establish that the tube integrity performance criteria will be met throughout the next operating period.

INTEGRITY ASSESSMENT

To understand the role of NDE in the integrity assessment of steam generator tubes, one must first understand the integrity assessment process. The integrity assessment process involves a comparison of the structural capacity of the tube with a structural integrity performance criterion. Figure 1 shows how the structural capacity of the tube is represented by a burst pressure relationship that describes the burst pressure as a function of the structural variable. The structural variable is a flaw or some other NDE-measured tube parameter whose presence and severity affect the pressure under which the tube will burst.

The burst pressure relationship can either be a derived equation, where possible, or an experimentally determined correlation. The performance criterion, as represented by a burst pressure leads to a limiting value for the structural variable. This means that to satisfy the performance criteria, the tube shall not contain a flaw that exceeds the structural limit. Flaws smaller than the structural limit can, in principle, exist in the tube without violating the performance criteria. The role of NDE is to determine the structural variable so that it can be compared against the requirement for burst pressure.

The relationship described by Figure 1 involves various uncertainties that must be accounted for. If the burst pressure relationship is derived from an equation, there would be no uncertainty in the equation itself. However, if the relationship is derived from experimental data, then the scatter of the data about the correlation curve determines a relational uncertainty. There are also uncertainties associated with material properties that need to be taken into account. NDE measurement uncertainties will further act to lower the condition monitoring limit that can be used to arrive at the structural limit. Once these uncertainties are accounted for, at appropriate confidence levels, the condition monitoring limit is obtained. This limit represents the value of the structural variable below which the tube meets the condition monitoring structural criterion. To look forward in time and do operational assessment, growth of the structural variable, in addition to uncertainties must be considered.

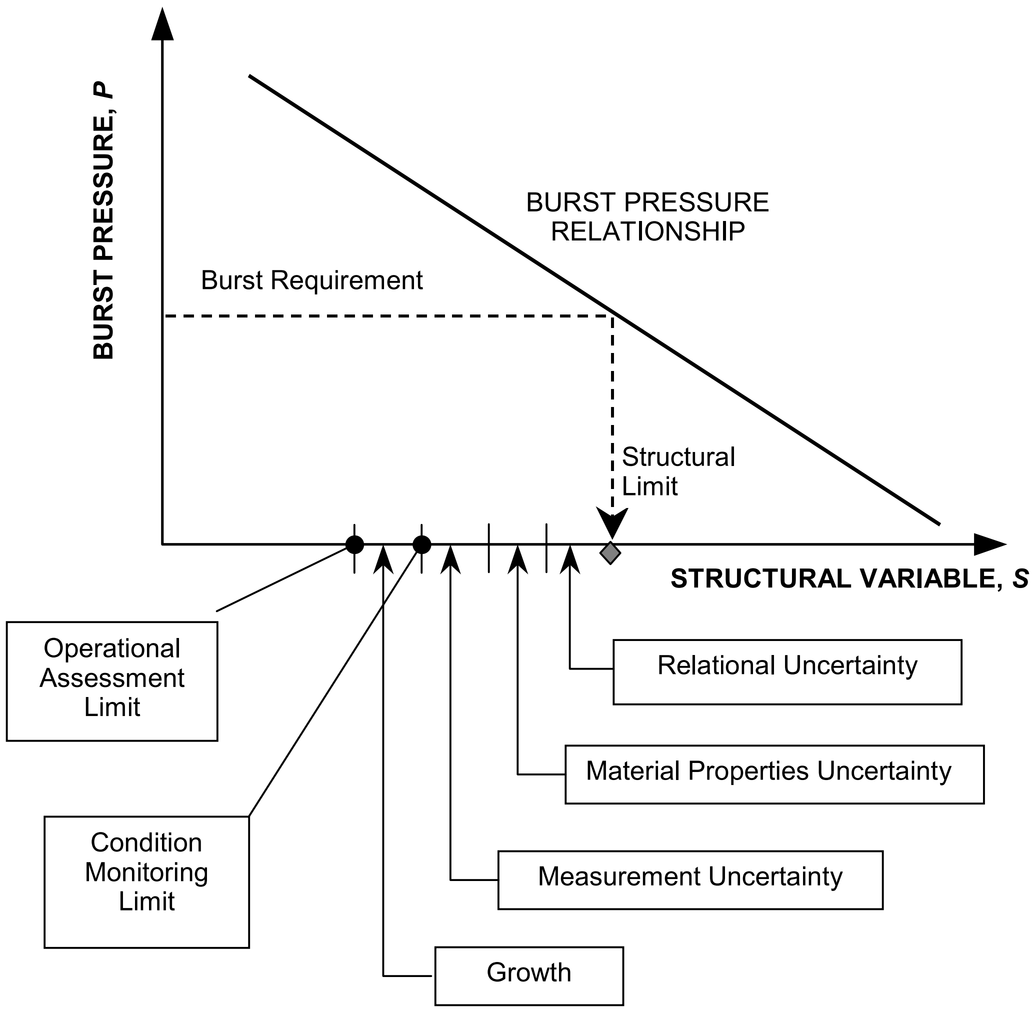

Figure 1. Relationship of Burst Pressure to Structural Variable
Effects of uncertainties in experimental correlations, material properties, NDE measurements, and flaw growth on condition monitoring and operational assessment limits of the structural variable

Figure 2 is a representation of the integrity assessment process and the role of NDE in it. Looking at the time line, the first step before the end of an operation cycle is degradation assessment which is performed in preparation for condition monitoring. Presence of known flaws and potential for new degradations are among the many factors that are considered in selection of sampling strategies and appropriate NDE techniques. Condition monitoring at the end of a just-completed operation cycle looks for growth of existing flaws and onset of new ones to verify that the performance criteria has not been violated during the last cycle. The findings of condition monitoring also serve to verify the

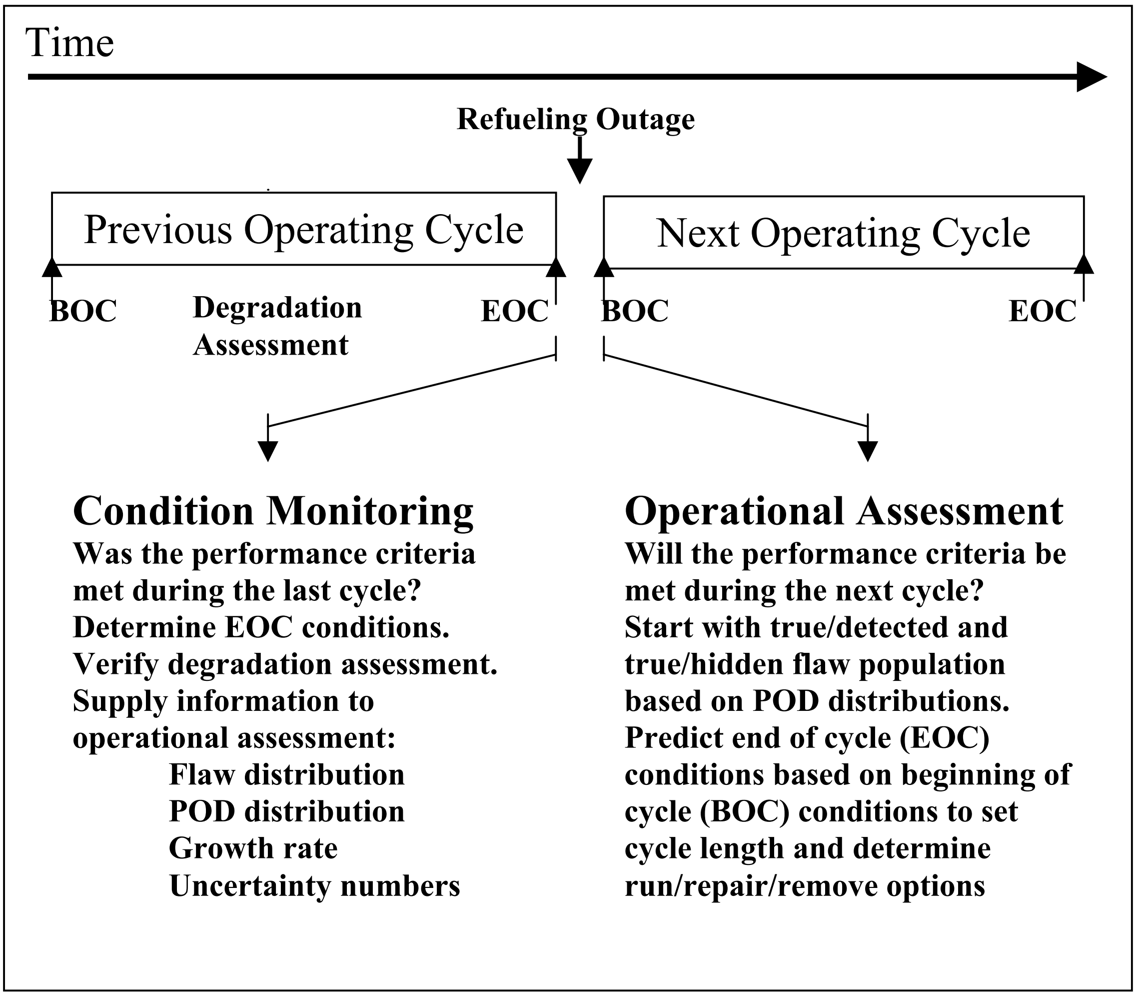

Figure 2. Elements of Integrity Assessment Process
Application of NDE deployed in condition monitoring, at end of cycle (EOC), and its relation to operational assessment, at beginning of cycle (BOC), to predict EOC conditions.

validity of the degradation assessment. Operational assessment uses NDE data from condition monitoring as input to establish the beginning of cycle (BOC) conditions and then adds the growth rate and other relevant considerations to determine the end of cycle (EOC) conditions. Prediction of EOC conditions then leads to decisions regarding cycle length and the specific run/repair/remove options for each tube. If condition monitoring at EOC shows that performance criteria have been violated, then it means that the previous operational assessment at BOC has been incorrect and its assumptions must be re-evaluated.

DETERMINATION AND DEMONSTRATION OF NDE CAPABILITIES

Methods of integrity assessments are characterized by their approach to combining of uncertainties. The strategies selected involve different levels of calculation complexity which in turn depend on the availability and quality of the leak correlation and NDE data with their associated uncertainties. The arithmetic method combines uncertainties by simply adding them, which while straightforward and simple, imposes a penalty in the form of a high level of conservatism on the determination of structural limit. The simplified statistical method combines uncertainties, represented by standard deviations, by summing the squares and taking the square root. The Monte Carlo method combines uncertainties by sampling and combining the distribution of uncertainties through Monte Carlo analysis.

In each of the above approaches what is needed is reliable NDE data and that has to come from demonstration and subsequent documentation of NDE capability with its associated uncertainties. The scope of the needed NDE documentation depends on the complexity of the integrity assessment approach and it ranges from simple mean values to distribution of values with their associated statistics and confidence levels.

NDE system capabilities and their associated uncertainties can be demonstrated and documented for the entire NDE system, although impractical and not exactly in accordance with field practice. Capabilities of techniques and human analysts are often documented separately and then combined to get the system performance parameters.

Traditional Approach to NDE Capability Determination and Demonstration

In traditional approaches to NDE for flaw detection, capabilities are described in terms of POD for specific flaw types and sizes. Flaw sizing capability of a particular technique and analyst pair is described in terms of a distribution of NDE measured values against true sizes as determined by metallurgical methods. Figure 3 shows a representation of sizing capability from which various statistical parameters such as standard deviation, error of regression, and correlation coefficient can be deduced.

EPRI Steam Generator Examination Guidelines [3] provides protocols for documentation of technique and analyst capabilities. The data obtained serves a dual purpose in qualifying techniques and analysts as well as providing POD and sizing information along with their associated statistics and uncertainties for integrity assessments.

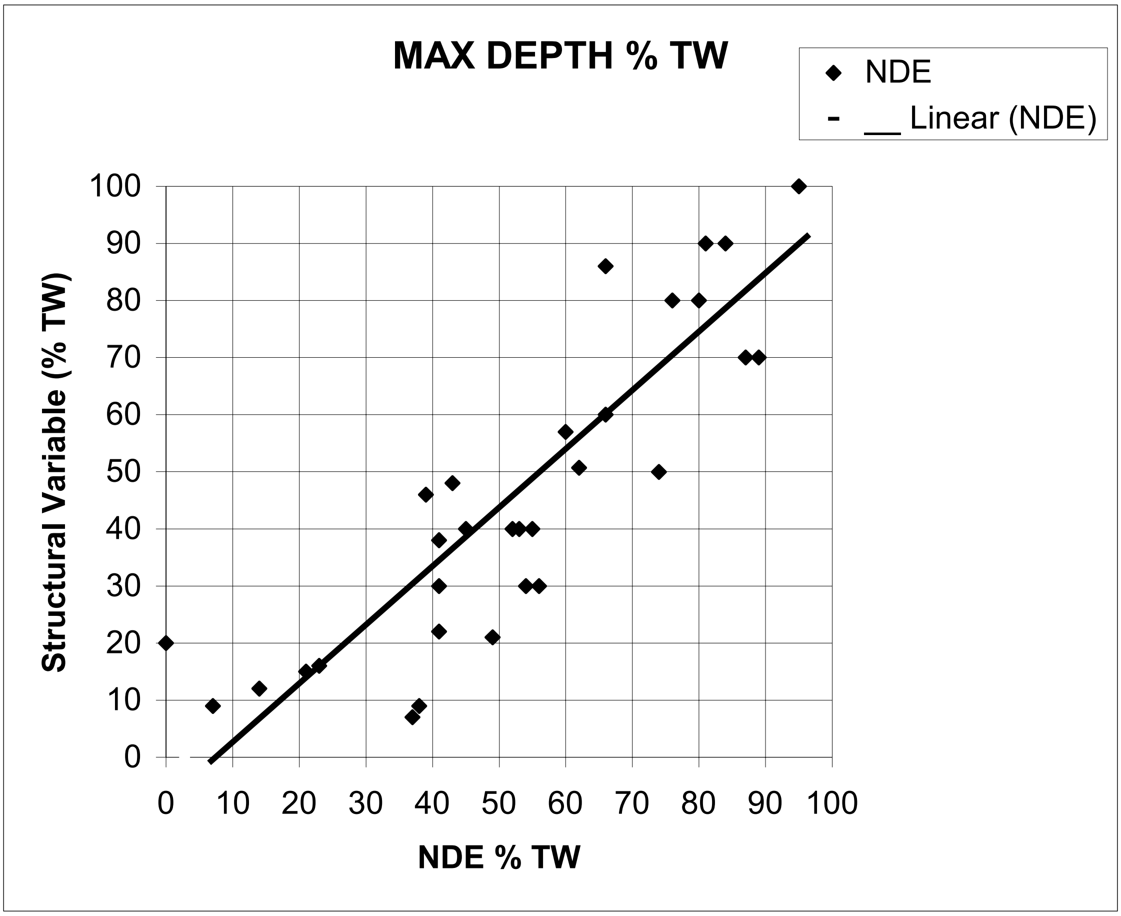

Figure 3. Documentation of NDE Sizing Capability
Structural variable can be any NDE measured parameter (length, depth, degraded area, etc.) , or in the above case the through wall (TW) depth of flaw as determined by metallugraphy. Regression analysis provides statistics and measures of uncertainties.

Effect of Noise on POD and Sizing Capabilities

Traditional approaches to performance demonstrations for eddy current inspection of SG tubes provide capability measures that are tied to the specific tube materials, defects, and general data sets from which they were derived. A POD derived from a relatively low-noise tube material and defects is not readily applicable to a plant with relatively high-noise tubes. While site-specific performance demonstrations (SSPD) are intended to check for differences in noise levels between the qualification data set and the filed conditions, they are at best qualitative and do not show the extent to which POD may be degraded at a particular region of interest – flaw location.

A number of SG events in recent years have amplified the need to account for tube noise and its effects on POD and sizing. EPRI has embarked on a program [4] to quantify the effects of tube noise on POD and sizing capability of eddy current tests. In many applications noise is often measured by the root-mean-square (RMS) value of its amplitude distribution. Eddy current signals and noise are in general vector quantities and as such are only completely described by knowledge of their respective magnitude and phase angles. Their interaction – in the context of noise addition and signal-to-noise ratio (S/N) calculations – is a vector process governed by vector algebra. Measurement of impedance plane peak-to-peak amplitude and phase angle allows for the determination of horizontal and vertical channel components which reduces a more complex interactive signal and noise vector process to two simpler scalar equations involving only addition and subtraction. In a typical inspection process POD is described as a function of a structural parameter without any dependence on signal to noise ratio (S/N).

POD as Function of S/N or Structural Parameter. Binary 0/1 (hit/miss) input for each indication is used in a generalized linear model (GLM) to develop POD distributions as a function of S/N or a structural parameter. The GLM regression analysis provides the nominal POD distribution and associated uncertainties for the distribution. In this approach, the hit/miss data for each data are weighted by the number of hits and misses available from performance testing of multiple analysts and teams. Figure 4 shows an example of POD vs. S/N derived from application of GLM.

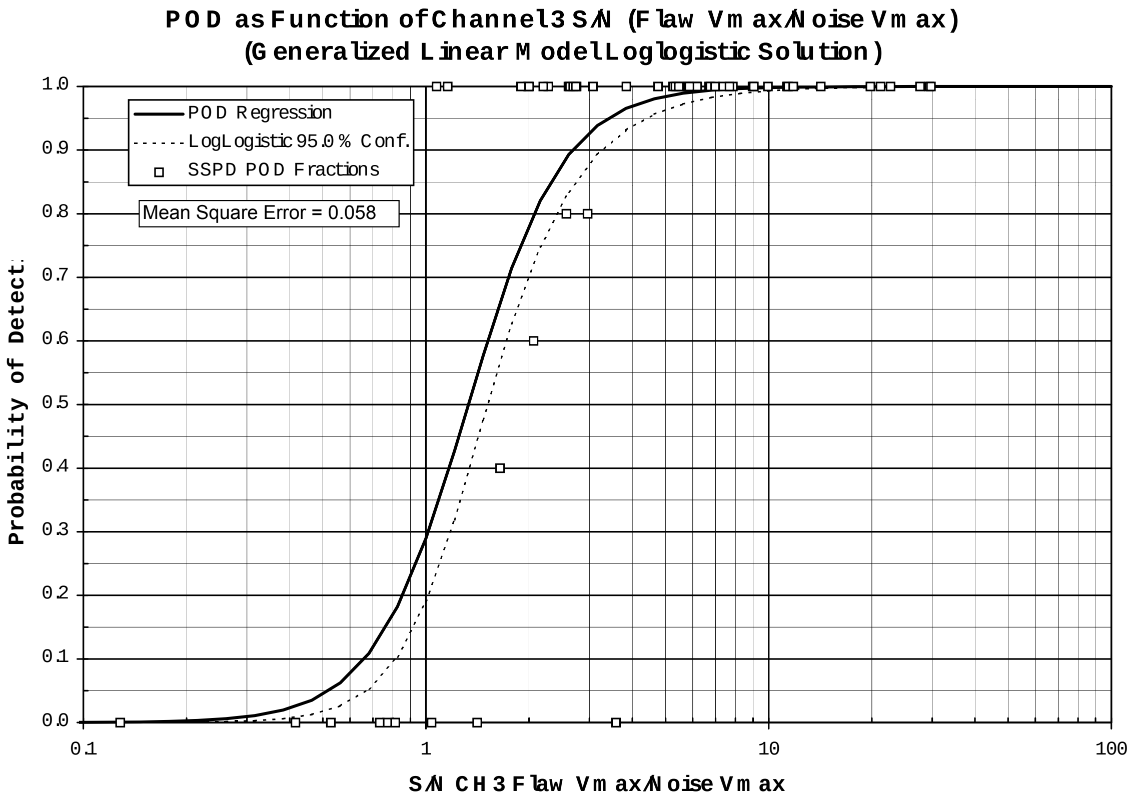

Figure 4. POD Versus S/N
An example of 2-D POD versus S/N derived from the application of GLM with hit/miss data from an SSPD

POD as Function of S/N and a Structural Parameter. Three dimensional POD distributions as a function of S/N and a structural parameter can also be derived from the GLM methods. The 3-D POD also uses hit/miss data weighted by the number of hits and misses for each indication in the database. Figure 5 shows and example of 3-D POD as function of a structural parameter (a running average maximum depth in this case) and S/N.

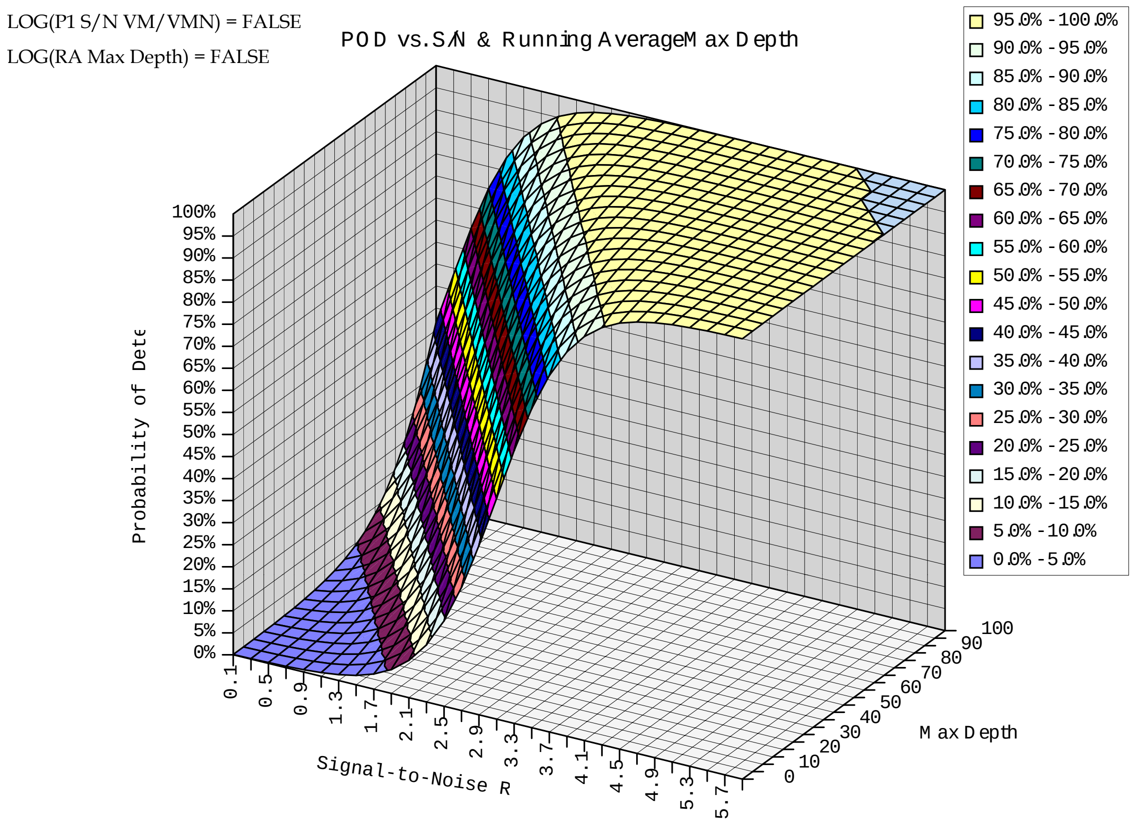

Figure 5. Three Dimensional POD as a Function of Structural Parameter and S/N.
An example of 3-D POD derived form the application of GLM to the hit/miss data in SSPD

What is desired is the development of POD distribution based on a specified noise distribution. Models are being developed that combine the use of two and three dimensional POD analysis methods with Monte Carlo method for varying noise levels used in the two dimensional POD distributions such as POD as a function of a structural parameter. These models allow for the determination of noise-adjusted POD as a function of a structural variable. Parametric studies need to be conducted to determine the sensitivity and range of uncertainties that can be associated with different methods of noise measurements.

CONCLUSIONS

The role of NDE in integrity assessment of steam generator tubes is to provide a means for condition monitoring and to provide the input for operational assessment to establish and determine that the performance criteria have been met in a just completed operation period and that they can be maintained throughout the upcoming operation of steam generators. The integrity assessment process demands that NDE have a focus and it places special requirements on it. It requires that the NDE provide a level of predictive capability that can only be established through performance demonstration. Flaw detection capabilities must be given in terms of POD distributions for various combinations of NDE techniques, flaw types, and flaw sizes at various locations along the steam generator tube. Flaw sizing capabilities must be given with their associated uncertainties for techniques and analysts as well as for the overall NDE system. Although currently a challenging problem in terms of methodology and implementation, effects of noise on POD and sizing capabilities must be established and accounted for in order to achieve a more realistic and robust steam generator tube integrity assessments.

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