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Evaluation of Sampling Plans for In-Service Inspection of Steam Generator Tubes

Comprehensive Analytical and Monte Carlo Simulation Results for Several Sampling Plans

Prepared by
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Operated by
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Prepared for
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Abstract

This report summarizes the results of three previous studies to evaluate and compare the effectiveness of sampling plans for steam generator tube inspections. An analytical evaluation and Monte Carlo simulation techniques were the methods used to evaluate sampling plan performance. To test the performance of candidate sampling plans under a variety of conditions, ranges of inspection system reliability were considered along with different distributions of tube degradation. Results from the eddy current reliability studies performed with the retired-from-service Surry 2A steam generator were utilized to guide the selection of appropriate probability of detection and flaw sizing models for use in the analysis. Different distributions of tube degradation were selected to span the range of conditions that might exist in operating steam generators. The principal means of evaluating sampling performance was to determine the effectiveness of the sampling plan for detecting and plugging defective tubes. A summary of key results from the eddy current reliability studies is presented. The analytical and Monte Carlo simulation analyses are discussed along with a synopsis of key results and conclusions.

Summary

This report summarizes the results of three previous studies to evaluate and compare the effectiveness of sampling plans for steam generator tube inspections. An analytical evaluation and Monte Carlo simulation technique were the methods used to evaluate sampling plan performance. To test the performance of candidate sampling plans under a variety of conditions, ranges of inspection system reliability were considered along with different distributions of tube degradation. Results from the eddy current reliability studies performed with the retired-from-service Surry 2A steam generator were utilized to guide the selection of appropriate probability of detection and flaw sizing models for use in the analysis. Different distributions of tube degradation were selected to span the range of conditions that might exist in operating steam generators. The principal measure of sampling performance was its effectiveness for detecting and plugging defective tubes. In this work a defective tube was defined as one with ≥ 75% throughwall degradation at the time of the inspection.

Significant results from this study are summarized below. This work clearly demonstrated that the most effective strategy for detecting and plugging defective tubes was 100% inspection. The effectiveness of all sampling plans relative to 100% inspection was found to depend on the number and distribution of degraded and defective tubes in the steam generator. All sampling plans were equally effective at detecting and plugging defective tubes when the defective tubes were surrounded by large numbers of degraded tubes. The notable exception to this finding was the standard technical specification sampling plan. The effectiveness of this sampling plan was highly erratic and did not always perform as well as the other sampling plans investigated, even when the defective tubes were surrounded by degraded tubes. When defective tubes were surrounded by a moderate number of degraded tubes the most effective sampling strategy was a 40% initial sample followed by expansion of the inspection around flaw indications found at the first stage. When defective tubes were completely isolated the most effective inspection strategy was 100% inspection. For isolated degradation the effectiveness of the sampling plans investigated was approximately linearly related to the initial sample size.

Inspection system reliability was found to impact sampling plan effectiveness significantly. Improving the probability of detection and flaw sizing reliability increased the effectiveness of all sampling plans studied. Improved flaw sizing reliability was found to produce greater increases in sampling plan effectiveness than improving the probability of detection, but this was probably caused by the specific differences in the probability of detection and flaw sizing curves considered in this study and may not be a general result.

A variant of the sampling plan given in the EPRI PWR Inspection Guidelines (EPRI-NP-6201) was found to be a very effective plan. This plan was effective largely because it expanded to 100% inspection almost every time. This plan consists of a 20% initial sample followed by 100% inspection of a "region" of the steam generator if one defective tube or more than 5% of the initial sample was found to be degraded. In this work the "region" for second-stage inspection was assumed to be all remaining tubes in the entire steam generator inspected full length. This is not the plan described in EPRI-NP-6201 so the results presented in this report represent an upper bound estimate of the potential effectiveness of that plan.

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1.0 Introduction

Eddy current (ET) inservice inspections of steam generator tubing are routinely performed as an element in the overall defense-in-depth strategy for ensuring the structural and leak-tight integrity of the reactor coolant pressure boundary. The main objectives of these inspections are to detect evidence of tube degradation so that corrective action(s) may be taken to mitigate tube damage, and to catch most or all degraded tubes that could fail by leak or burst before the next inspection. To attain these objectives a reliable inservice inspection (ISI) must be performed. An element of the process which determines, in part, the overall effectiveness of the inspection is the selection of tubes from the total tube population for inspection. There are two approaches to the selection of tubes for inspection. The first approach is to select all of the tubes or 100% inspection. This approach is the most effective means for identifying tubes which might fail between ISIs, but may, in some cases, place an economic burden on utilities for marginal gain in safety or operational reliability. The second approach is to select a subset of the tube population for an initial inspection and use the results of that initial inspection to decide if further inspection is needed (i.e. to "expand" the initial inspection). With this approach there is no guarantee that all tubes with "significant" flaws will be inspected. The effectiveness of the inspection is limited, in this case, by the number of tubes selected for initial inspection, the reliability of the inspection equipment, personnel, and procedures, and the level and distribution of degradation in the steam generator which in conjunction with the inspection system reliability determines the total number of tubes inspected.

The objective of this work was to evaluate and compare sampling plans for the primary or general monitoring ISI. The goal of the primary ISI is to detect any form of tube degradation occurring at any location in the steam generator tube bundle. The evaluations performed were not actual ISIs but consisted of exercising an analytical model or performing Monte Carlo computer simulations of ISIs. This report summarizes the methodology employed, the results obtained, and the conclusions reached from three previous studies. In the first study (Bowen et al. 1989) the eddy current reliability information and evaluation methodology were developed under the NRC-managed Steam Generator Tube Integrity Program. A follow-on effort (Hanlen 1990) was conducted under funding from the Electric Power Research Institute (EPRI) and was jointly sponsored by EPRI and the NRC. The objective of this effort was to evaluate additional sampling plans not considered in the first effort. In particular the sampling plan given in the standard plant technical specifications was evaluated as part of this study. In the final effort[1], Monte Carlo simulation techniques were utilized to evaluate a sampling plan that was similar to the one recommended in the EPRI PWR Steam Generator Examination Guidelines, Revision 2, NP-6201.

Four types of sequential (two-stage) sampling plans were evaluated and compared. Sequential sampling plans involve the selection of an initial sample of tubes for inspection. Depending on the inspection results from the initial sample (i.e. the "expansion rules") the scope of the inspection may be expanded by selecting additional tubes. The first type of sampling plan evaluated was a systematic-sequential plan. In this plan an initial sample of tubes is selected for inspection by superimposing a grid over the tube-sheet array. For example, in a plan involving a 20% initial sample every fifth tube in the steam generator is inspected. The results of the initial sample are used to determine if additional tube inspections should be performed. In this work, additional tubes were inspected if a tube inspected at the first-stage was found to have any ET flaw indication. An ET flaw indication was defined as one with some through-wall depth. Inspection was expanded radially around the tube with the ET flaw indication until a two tube wide "buffer zone" was observed. The buffer zone consisted of tubes free of any ET flaw indications and completely surrounded the tube which triggered the expansion. The second type of sequential sampling plan evaluated was exactly the same as the first type in all aspects except the initial sample of tubes was selected randomly rather than systematically. The third type of sampling plan was the standard technical specification (STS). In this plan the initial sample consists of 3% of the tube population, which is chosen randomly. Second-stage inspection depends on the results of the initial sample. Different levels of second-stage inspection are performed depending on whether the results of the first-stage inspection are categorized as C-2, or C-3. This categorization depends

[1]Heasler, P. G., R. J. Kurtz, and D. B. Baird. 1992. *Evaluation of Steam Generator Two-Stage Sampling Plans by Analytical Methods and Monte Carlo Simulation.* PNWD-2004, Battelle, Pacific Northwest Laboratories, Richland, Washington.

on the numbers of degraded and/or defective tubes discovered in the initial sample. The last sampling plan evaluated was a variant of one proposed by EPRI. This sampling plan consisted of a systematically selected initial sample (20%, 33.3%, or 40%) followed by second-stage inspection consisting of all remaining tubes in the steam generator. Second-stage inspection was triggered if one or more tubes in the initial sample was classified as defective or if 5% or more of the initial sample of tubes was classified as degraded.

It should be noted for all the sampling plans evaluated in this report we have reduced an essentially three-dimensional inspection problem to two-dimensions. In other words, we assume that the "inspection unit" is an entire tube and not a region of a tube as it often is in actual practice. This approach was taken because the objective of this study was to evaluate primary or general monitoring ISIs. The goal of the primary ISI is to detect tube degradation at any location in the tube bundle so the logical "inspection unit" is the entire tube. The above comments are particularly important in regard to the evaluations performed based on or with the EPRI sampling plan. In the actual EPRI sampling plan second-stage inspection consists of 100% of the "region" of interest. In our evaluations we have assumed that if second-stage inspection was triggered, then all remaining tubes in the steam generator were inspected full length. This is not part of the EPRI sampling plan. The EPRI plan allows for limited second-stage examination depending on the type of steam generator, the tube damage mechanism, and plant history. A potential source of inspection unreliability exists in attempting to limit the extent of second-stage inspection. We have not included this source of unreliability in our calculations so the results given in this report should be considered an upper-bound estimate of the effectiveness of the EPRI sampling plan.

All of the sampling plans evaluated in this report assumed that the inspection always produces information on detection and sizing of flaws for each tube inspected. The consequences of a tube inspection are very specific. If a flaw is detected and sized above the plugging limit, the tube is either plugged or repaired.

The objective of the inspection is to detect evidence of tube degradation and to identify all defective tubes which could fail by leak or burst during reactor operation. In this work a defective tube was defined as one with a true level of degradation ≥ 75% deep. This definition was based on empirical correlations of tube failure pressure versus flaw depth for flaws greater than one tube diameter in axial length, and includes a 10% depth allowance for flaw growth between inspections. This flaw size corresponds to one which could lead to tube failure under main-steam-line-break loading conditions.

One criterion for comparing sampling plans is the probability of detecting and plugging defective tubes. For a given tube, this probability is a function of two other probabilities: (1) the probability of detection (POD), which is the probability of observing a positive ET indication, and (2) the conditional probability, denoted by PEL, that a positive ET indication 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 reliability of the inspectors, their equipment, and the procedure employed.

In order to perform sampling plan evaluations two pieces of information must be specified; the inspection system performance parameters as characterized by the POD and PEL models and the true state distribution of degradation in the steam generator. True state degradation distributions consisted of a number of hypothetical "tube maps" specifying the number and distribution of degraded and defective tubes in the steam generator. Each tube was either unflawed or contained one flaw of a certain size. The output of an evaluation produced the total number of tubes inspected and the number of defective tubes detected and plugged. These two results formed the basis for generating other statistics for comparing the various sampling strategies.

Section 2 of this report describes statistical analyses of round robin data to characterize ET sizing error and POD performance. This information was used to select appropriate ET sizing models and POD curves for use in the sampling plan evaluations. Section 3 presents the results of an analytical evaluation performed to compare the effectiveness of 20% and 40% systematic-sequential sampling plans with 100% inspection for one particular distribution of degradation. Section 4 gives the results of Monte Carlo simulations performed to supplement the analytical evaluation. Monte Carlo simulation techniques permitted evaluation of a range of ET system performance characteristics and a spectrum of degradation distributions ranging from isolated defective tubes up to substantial clustering of degraded and defective tubes. Finally, the conclusions from this study are described in Section 5.

2.0 ET Sizing Error and Probability of Detection

This section summarizes the results of statistical analyses and modeling performed to characterize POD and ET sizing error. The inspection data from the Steam Generator Group Project (SGGP) Bradley et al. 1988 were used to guide the selection of appropriate POD curves and PEL models for use in the sampling plan evaluations. Because multiple inspection teams were involved, statistical modeling was used to develop 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 the various sampling plans. The SGGP results are largely due to wastage and pitting type flaws, but the models of POD and PEL developed from these data are completely general. The results in this report do not relate just to wastage and pitting type flaws but are applicable to any form of tube degradation for which the ET system POD and sizing performance characteristics can be represented by our statistical models.

2.1 Modeling ET Sizing Error

For the purpose of characterizing ET sizing error and estimating PEL values, results from the SGGP round robin studies were utilized. Destructive metallographic analyses of tube segments removed from the Surry Steam Generator were matched with the ET inspection results for 12 participating teams. Only the inspection data for the hot-leg top-of-tubesheet were used for this analysis since this is the region where most of the defects were located in the steam generator and where the vast majority of the metallographic analyses were performed. Because PEL is conditional upon a positive ET indication, the data set for each team was reduced by removing all false calls and nondetections.

Figure 2.1 shows the relationship between ET estimated defect depth and metallographic examination results for a typical inspection team using conventional multi-frequency inspection equipment and procedures. The best correlation observed is shown in Figure 2.2. This team used complementary inspection equipment and specially developed frequency mixes to augment their conventional inspection results to achieve improved flaw sizing accuracy and precision.

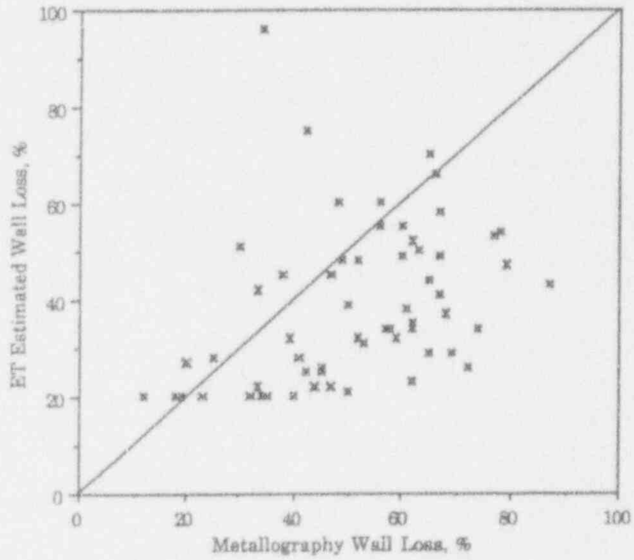

Figure 2.1 Sizing Results for Typical Team From Surry Steam Generator Study

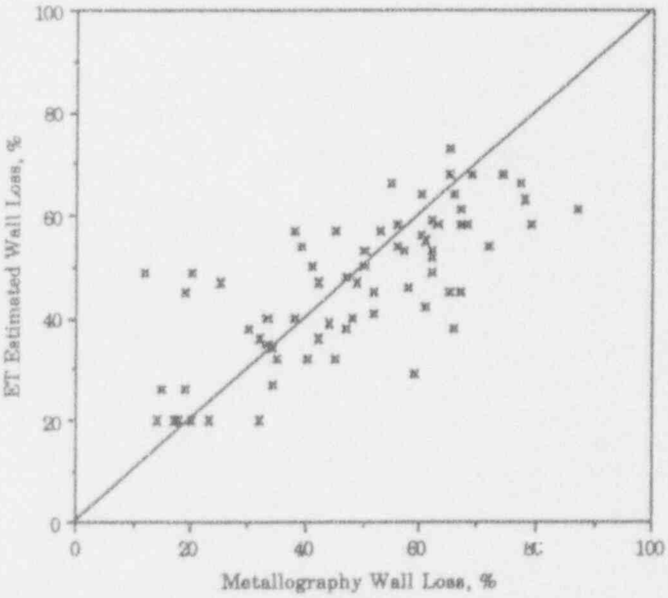

Figure 2.2 Sizing Results for Best Performing Team From Surry Steam Generator Study

The statistical methodology used to model ET sizing error is based on the following definitions and assumptions. For a particular team and a particular flaw, define:

X = "True" maximum flaw depth determined from destructive examination (DE),

Y = Observed flaw depth as determined from ET inspection.

Assume Y can be modeled as a simple linear function of X but with random error e, so that

$$Y = a + bX + e \tag{2.1}$$

That is, at a specified value of X, the distribution of Y is assumed to have true mean a + bX and variance Var(e), where a, b, and Var(e) are unknown parameters that must be estimated for each team from the inspection data.

The iterative regression algorithm presented by Aitkin (1981) was used to fit the model in Equation 2.1 to the inspection data for each team. This technique is designed to fit models to data with censored observations and produces estimates of a, b, and Var(e). Selected results from this analysis are given in Table 2.1. The columns labeled a, b, and Var(e) display the estimates of these parameters. The SD (or standard deviation) column displays the square root of the estimate of Var(e). Note that the estimate of Var(e) is a measure of the variability of the ET values about the fitted line. The #-Obs column is the number of (X,Y) pairs that are present for each team. Table 2.1 is divided into three sections, corresponding to "groups" of teams. It should be noted that an "ideal" team would have a = 0, b = 1, and Var(e) would be small.

Table 2.1. Summary of Individual Team Flaw Sizing Regression Results

Team	a	b	Var(e)	SD	#-Obs	
A	13.59	0.44	285.00	16.88	61	Data Acquisition and Analysis Round Robin
B	15.69	0.40	220.34	14.84	48	
C	25.17	0.37	254.58	15.96	59	
D	10.32	0.57	294.41	17.16	61	
E	22.02	0.40	217.24	14.74	61	
U	-4.67	0.85	61.83	7.86	18	Advanced/Alternate Techniques Round Robin
UU	38.30	0.15	334.47	18.29	28	
V	12.60	0.68	105.90	10.29	72	
VV	20.26	0.24	329.88	18.16	28	
W	-7.90	1.01	426.92	20.66	14	
X	7.73	0.51	244.96	15.65	62	Baseline
Y	11.85	0.51	323.45	17.98	76	

2.2 Probability of Exceeding ET Plugging Limit

It is of interest to estimate the probability that a non-zero ET value will exceed a specified "plugging limit" T for a flaw with "true" depth X. It is also of interest to determine an ET plugging limit such that the probability of plugging or repairing defective tubes is acceptably high. The fitted linear models described previously provide a means for achieving these objectives.

For a particular fitted model and specified ET plugging limit T, the probability of exceeding the ET plugging limit for a tube with a positive ET indication and a flaw with "true" depth X can be evaluated as follows. The predicted mean ET value is computed from the formula $Y = a + bX$ with the estimates of a and b substituted. The variance of the distribution of ET values at X is the sum of the estimate of Var(e) and the variance of the predicted ET mean value. The probability that an observed ET value will exceed T is estimated from the normal distribution with mean and variance set equal to their estimated values. In other words

$$Pr(PEL|X) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{(T-a-bX)/SD} \exp\left(\frac{-z^2}{2}\right) dz \quad (2.2)$$

For this work definitions of degraded and defective tubes were needed to facilitate the evaluation of sampling plan effectiveness and to determine when to trigger second-stage inspection. Consequently, a defective tube was defined as one which contains a flaw of such severity that the tube is unacceptable for continued service. A degraded tube was defined as one which contains a flaw of lesser severity than a defective tube. In terms of through-wall flaw depth, a defective tube was taken as one with through-wall degradation severe enough to cause tube failure by burst or leakage under normal operating or accident loading conditions. To determine the through-wall flaw depth which would result in a tube being classified as defective, test data on tube failure pressure as a function of flaw size and geometry were utilized (Alzheimer et al. 1979 and Kurtz et al. 1991).

The burst mode constitutive equations were used to develop a definition of an unacceptable flaw. These equations show than an 85% through-wall flaw represents an average depth for all flaw types that could fail under main-steam-line-break loading conditions ($\approx$2600 psi pressure differential). If a flaw growth rate of 10% per operating cycle is assumed, then a tube with an actual flaw $\geq$ 75% through-wall flaw could fail under main-steam-line-break loading conditions by the end of the next operating period. This level of degradation was used to define an unacceptable (i.e., defective) tube condition requiring tube plugging or repair.

If it is assumed that the ET plugging limit is 40%, the estimated PEL values (probability that $Y > 40\%$ given that $X \geq 75\%$) for the fitted models are displayed in Table 2.2. For example, when a tube has a flaw with true depth $X = 75\%$, and a non-zero ET value has been observed by a team with sizing characteristics like the average of the Data Acquisition and Analysis Round Robin (DAARR) teams, the probability is 0.73 that the observed ET value will be greater than

Table 2.2. Estimated PEL Values for $X = 75\%$ and $T = 40\%$

Team	PEL	
A	0.65	Data Acquisition and Analysis Round Robin
B	0.65	
C	0.79	
D	0.78	
E	0.79	
U	0.99	Advanced/ Alternate Techniques Round Robin
UU	0.70	
V	0.99	
VV	0.46	
W	0.91	
X	0.65	Baseline
Y	0.71	

Table 2.3. Estimated PEL Values for Three Plugging Limits

Plugging Limit, %	True Depth, %	Team A	Team UU	Team V
T = 30	0	0.17	0.68	0.05
	20	0.33	0.73	0.36
	40	0.53	0.78	0.83
	60	0.72	0.83	0.99
	75	0.84	0.86	1.00
	100	0.95	0.90	1.00
T = 40	0	0.06	0.46	0.00
	20	0.15	0.53	0.09
	40	0.30	0.59	0.49
	60	0.50	0.66	0.90
	75	0.65	0.70	0.99
	100	0.85	0.77	1.00
T = 50	0	0.02	0.26	0.00
	20	0.05	0.32	0.01
	40	0.13	0.38	0.16
	60	0.28	0.44	0.63
	75	0.42	0.49	0.91
	100	0.67	0.57	1.00

T = 40%. Clearly, a range of sizing capabilities is represented by the various models.

The sizing capabilities of the teams can be compared by comparing the fitted models for each team or by comparing PEL values. For example, Table 2.3 displays PEL values for three of the teams with plugging limit values T = 30%, 40%, and 50%.

Note that Team UU always has higher PEL values for nondefective tubes ($X < 75\%$) than the other teams. If the plugging limit is set at T = 30% so that Team A and Team UU have a high PEL when X = 75%, all teams have PEL > 0.5 when X > 40%; and Team UU would tend to plug most of the tubes with positive ET indications. If T is increased to 50%, Team V has a high PEL when X = 75%, and would not be likely to plug tubes with true flaw depth $X < 40\%$; but Team A and Team UU have low PEL values when $X = 75\%$.

2.3 Probability of Detection

The results from the SGGP round robin studies were utilized to guide the selection of POD curves to represent a range of NDE system flaw detection reliabilities. Idealized POD curves were used for the sampling plan evaluations described in this report. These curves are presented in Section 4. The idealized curves are intended to represent overall NDE system POD performance for the range of flaw types that might be encountered during an ISI. Even though almost all of the SGGP data pertain to pitting and/or wastage-type defects, the sampling plan evaluation results do not depend explicitly on the flaw type. The results of the work described in this report apply to any NDE inspection system exhibiting the POD characteristics shown in Section 4. To give the reader an understanding of the reasons for selecting the idealized POD curves used in our analysis, an overview of the POD results from the SGGP is presented below.

Estimates of POD were obtained from the SGGP data by matching ET inspection results with the results from both the visual inspections and destructive examinations of tubes removed from the Surry Steam Generator. For each "true flaw size" category, the number of nonzero ET indications divided by the total number of flaws was used as a POD estimate. A POD curve (i.e., a plot of estimated POD versus "true size") was constructed for each inspection team, and an overall POD curve was constructed by combining the data from the DAARR and Baseline teams. The ranges of estimated POD values were used as a basis for evaluating and comparing the performance of sampling plans.

The curve shown in Figure 2.3 gives the average POD performance for seven teams employing conventional Zetec MIZ-12 multi-frequency inspection and DDA-4 analysis equipment. The curve was based on metallographic measurement of the maximum wall-loss for defects from all regions of the steam generator combined. The oscillatory behavior of the curves is due to the small numbers of specimens in each of the incremental wall-loss categories.

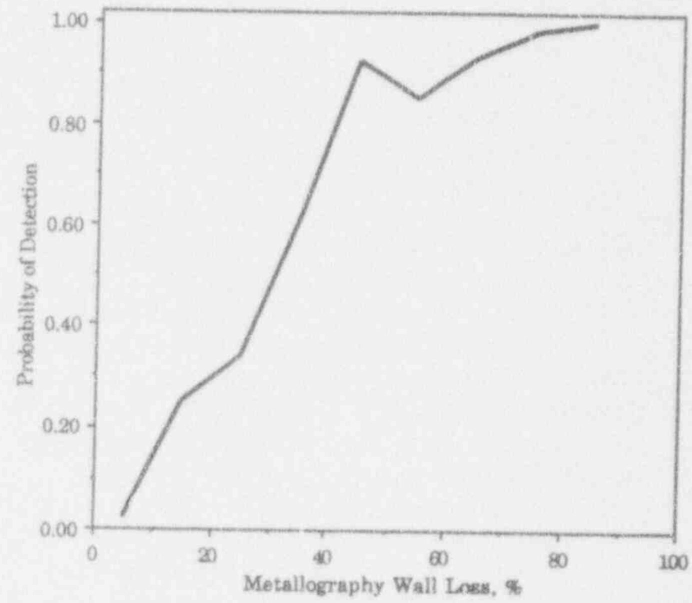

Figure 2.3. Average POD Performance for Surry Round Robin Teams

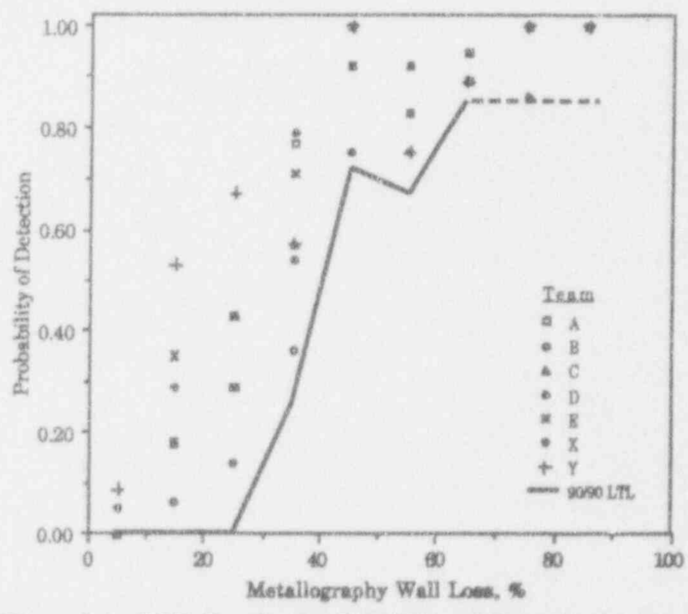

Figure 2.4. POD Results for DAARR and Baseline Teams from the Surry Round Robins

Figure 2.4 is a plot of the individual POD estimates for the same seven teams used to develop Figure 2.3. The curve in Figure 2.4 is an approximate 90/90 lower tolerance limit (LTL) for these teams. The teams are assumed to be typical of the total population of teams performing inservice inspection; therefore, if each team in the total population of teams performing inservice inspection had inspected the round robin tube set, we can be 90% confident that 90% of the individual team POD values would be above the LTL. Note that the part of the curve extending 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 ≥ 65%.

As shown in Figure 2.5, an apparent improved POD performance was observed for one team that employed alternative inspection methods. The POD curve for this team increased more rapidly at low levels of wall-loss and was higher above 40% wall-loss than the POD curves for other teams. This team employed specially developed frequency mixes to enhance the signal-to-noise ratio and computer data screening techniques.

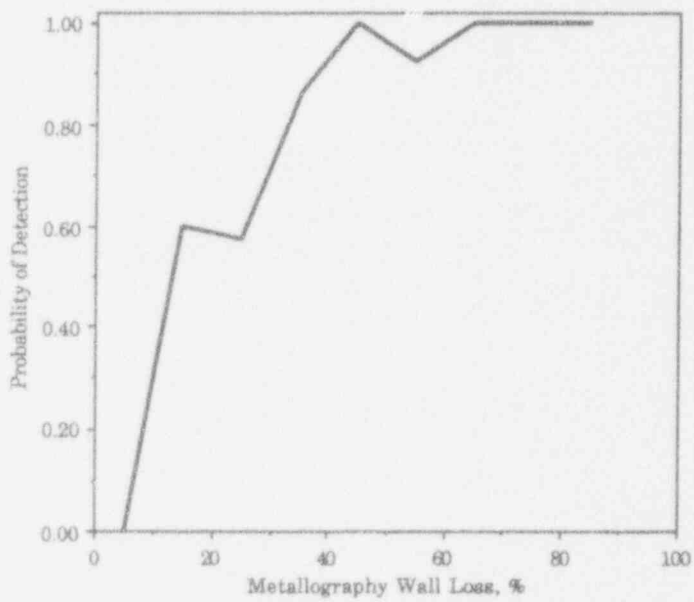

Figure 2.5. Best POD Performance Observed from Surry Round Robin

3.0 Analytical Evaluation and Comparison of Sampling Plans

Two statistical evaluation techniques were used to determine the effectiveness of sampling plans for detecting and plugging defective tubes. The first technique consisted of an analytical evaluation which is discussed in this section. In the analytical evaluation, concepts from sampling theory and probability theory are utilized. The evaluation was based on the ranges of POD and PEL values estimated from the SGGP data. The second technique involved Monte Carlo simulations to further evaluate and compare sampling plans under more realistic conditions. The Monte Carlo simulation methods and results are presented in Section 4.

There are two basic strategies for selecting tubes from a generator for ISI. Either all tubes are inspected (100% inspection) or a sample of the tubes is selected for inspection. Although there are many possible sampling plans that could be applied, several types of sequential sampling plans were identified as most appropriate for analytical evaluation and were evaluated and compared with 100% inspection.

In evaluating and comparing the expected effectiveness of sampling plans for detecting and plugging (or repairing) defective tubes, it is important to recognize that the effectiveness of 100% inspection is the maximum achievable and provides an upper bound for the effectiveness of all sampling plans. Thus, it is of interest to evaluate the effectiveness of 100% inspection and then use the results as a basis for evaluating and comparing the effectiveness of sampling plans.

With 100% inspection, all defective tubes in a generator will be inspected. The inspection of each defective tube is assumed to be independent of the inspection of all other defective tubes. Therefore, the effectiveness of 100% inspection does not depend on the distribution of defective tubes within the generator. For the 100% inspection case, the joint probability, p, of detecting and plugging an individual defective tube is the product of the POD and the PEL for a defective tube. That is,

$$p = POD(PEL) \qquad (3.1)$$

It is assumed that POD = 0.9 for flaws large enough to classify a tube as defective, then p can be computed from Equation 3.1 for a specified PEL value. For the purpose of evaluating 100% inspection and using the results as a basis for evaluating and comparing the performance of sampling plans, PEL values ranging from 0.50 to 1.0 were used in Equation 3.1 to compute the values of p shown in Table 3.1.

Table 3.1. Values of p Computed from the Given PEL Values by Assuming POD = 0.9

PEL	p
0.50	0.45
0.60	0.54
0.70	0.63
0.80	0.72
0.85	0.77
0.90	0.81
0.95	0.86
1.00	0.90

When a sampling plan is applied to select tubes for inspection, there is no guarantee that all defective tubes in a generator will be inspected. Thus, the probability of detecting and plugging a defective tube is a function of the probability that the defective tube will be inspected. Without further assumptions about the distribution of defective tubes in a generator, Equation 3.1 would be multiplied by the probability of inspection. For example, if POD = 0.9, PEL = 0.7, and if 3% of the tubes are randomly selected for inspection, then the probability of inspecting, detecting, and plugging an individual defective tube is $p = 0.9(0.7)(0.03) = 0.0189$. With 50% random sampling, $p = 0.9(0.7)(0.5) = 0.315$. These values compare with $p = 0.9(0.7)$ for 0.63 for 100% inspection. By making assumptions about the distribution of defective tubes and by considering particular types of sequential sampling plans, the effectiveness of sampling/inspection relative to 100% inspection can be improved considerably over the completely random sampling implied above.

In the analytical work it was assumed that defective tubes tend to occur in "clusters," which are groups of defective and degraded tubes. For the purpose of evaluating and comparing sampling plans, a "minimum" cluster was assumed, which is a defective tube surrounded by degraded but not defective tubes in the following pattern:

```
 D
DFD
 D
```

where F denotes a defective tube and D denotes a degraded but not defective tube.

It is recognized that in a real generator, clusters could be shaped differently than the one shown above, and could be different sizes, and could include more than one defective tube. The above cluster configuration was selected for evaluation purposes because it would be harder to detect than a larger cluster with more than one defective tube. It is also recognized that in some cases a defective tube may be isolated. Thus, in the Monte Carlo simulation portion of this study, various distributions of degraded and defective tubes were examined to evaluate other conditions of clustering ranging from nearly isolated defectives up to a single large cluster.

The sequential sampling plans that were chosen for analytical evaluation are assumed to proceed as follows:

(a) The initial sample is selected according to a systematic sampling plan that consists of a specified percentage of the tubes in a generator, and each tube in the sample is inspected.

(b) When a positive ET indication is observed, inspection continues in the region immediately surrounding the suspect tube until a two-tube wide "buffer zone" is observed, which is composed of tubes with no ET indications, and which completely surrounds the tube(s) with ET indication(s).

(c) In steps (a) and (b), each tube with an ET indication that exceeds the plugging limit will be plugged or repaired.

By assuming the above cluster configuration, it is possible to define a 20% systematic sampling plan for step (a) that would include exactly one tube from each cluster. It is also possible to define a 40% systematic sampling plan that would include exactly two tubes from each cluster. Examples of 20% and 40% systematic sampling grid patterns that produce this result are shown in Figures 3.1 and 3.2, respectively. Then, if the defective tube in a cluster is not included in the initial sample, there is a chance that the degraded tube(s) will produce a positive ET indication that will trigger additional inspection (step b), which will include the defective tube. Thus, the probability of inspecting and detecting the defective tube, denoted by PI&D, is a function of the POD for degraded but not defective tubes, denoted by POD(deg), as well as the POD for defective tubes (which is assumed to be 0.9).

```
X0000X0000X0000X0000X0000
00X0000X0000X0000X0000X00
0000X0000X0000X0000X0000X
0X0000X0000X0000X0000X000
000X0000X0000X0000X0000X0
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0000X0000X0000X0000X0000X
0X0000X0000X0000X0000X000
000X0000X0000X0000X0000X0
```

Figure 3.1. Example of a 20% Systematic Sampling Grid Pattern Where Exactly One Tube from Each Cluster Would be Included in the Initial Sample

```
XX000XX000XX000XX000XX000
000XX000XX000XX000XX000XX
0XX000XX000XX000XX000XX00
X000XX000XX000XX000XX000X
00XX000XX000XX000XX000XX0
XX000XX000XX000XX000XX000
000XX000XX000XX000XX000XX
0XX000XX000XX000XX000XX00
X000XX000XX000XX000XX000X
00XX000XX000XX000XX000XX0
```

Figure 3.2. Example of a 40% Systematic Sampling Grid Pattern Where Exactly Two Tubes from Each Cluster Would be Included in the Initial Sample

It should be noted that in actual implementation of a systematic sampling plan, the grid should be "shifted" at each ISI so that every tube in a generator will eventually be inspected.

With the 20% systematic sampling plan shown in Figure 3.1, exactly one tube from each cluster is inspected at the first stage of inspection, and an expression for PI&D for an individual defective tube is derived as follows:

A. POD = 0.9 for a defective tube

B. Pr(defective tube is inspected at first stage) = 0.2

C. POD(deg) = Pr(ET > 0 | degraded but not defective tube)

D. Pr(a degraded tube is inspected at first stage) = 0.8

E. Pr(inspect defective at first stage and observe ET > 0) = A(B) = 0.18

F. Pr(inspect degraded at first stage and observe ET > 0) = C(D) = (0.8)POD(deg)

Detecting a degraded tube at the first stage would trigger the second stage of inspection that would include the defective tube. Therefore,

G. Pr(ET > 0 for def at second stage | ET > 0 for deg at first stage) = 0.9

Then,

$$\begin{aligned} PI\&D &= Pr(\text{inspect and detect defective at first or second stage}) \\ &= E + F(G) \\ &= 0.18 + (0.8)(0.9)[POD(deg)] \\ PI\&D &= 0.18 + 0.72[POD(deg)] \qquad (3.2) \end{aligned}$$

With the 40% systematic sampling shown in Figure 3.2, exactly two tubes from each cluster are inspected at the first stage of inspection, and an expression for PI&D for an individual defective tube can be derived in a manner similar to the development given above (Bowen et al. 1989). For the 40% plan, the expression for PI&D is:

$$PI\&D = 0.36 + 1.116\ POD(deg) - 0.54\ [POD(deg)]^2 \qquad (3.3)$$

The joint probability of detecting and plugging a defective tube is given by

$$p = PI\&D(PEL) \qquad (3.4)$$

For evaluating and comparing the sequential sampling plans and 100% inspection, PEL values ranging from 0.50 to 1.0 were considered (the PEL estimates from the fitted ET sizing data range from 0.46 to 0.99), together with values of POD(deg) ranging from 0.5 to 0.7. For the sequential sampling plans with 20% or 40% initial sampling, values of p were computed from Equation 3.4. The resulting values of p are displayed in Table 3.1. For 100% inspection, values of p were computed from Equation 3.1 by assuming POD = 0.9.

Note in Table 3.1 that when POD(deg) = 0.7, the sequential sampling plan with 40% systematic sampling at the initial stage yields values of p that are close to those obtained for 100% inspection. In fact, by setting Equations 3.2 and 3.3 equal to 0.9 and then solving for POD(deg), a value of POD(deg) = 1.0 would be required for the 20% sequential plan to perform exactly like 100% inspection, whereas POD(deg) = 0.77 would be required for the 40% sequential plan to perform exactly like 100% inspection. Numerous tables were computed for each of the three plans which display the probability of leaving a specified number of defective tubes unplugged after inspection when there are n (n ranged from 2 to 20) defective tubes in the generator prior to inspection. These results indicate that when POD(deg) is approximately 0.7, the 40% sequential plan nearly duplicates the performance of 100% inspection. It must be emphasized, however, that these results are dependent upon the cluster assumption discussed previously.

Table 3.1. Values of *p* for a Range of PEL and POD(deg) Values Assuming that POD = 0.9 for Defective Tubes

		PEL							
		0.50	0.60	0.70	0.80	0.85	0.90	0.95	1.00
		20% Sequential							
	0.50	0.270	0.324	0.378	0.432	0.459	0.486	0.513	0.540
POD(deg)	0.60	0.306	0.368	0.428	0.490	0.520	0.551	0.581	0.612
	0.70	0.342	0.410	0.479	0.547	0.581	0.616	0.65C	0.684
		40% Sequential							
	0.50	0.392	0.470	0.548	0.626	0.666	0.705	0.744	0.783
POD(deg)	0.60	0.418	0.501	0.585	0.668	0.710	0.752	0.793	0.835
	0.70	0.438	0.526	0.614	0.701	0.745	0.789	0.833	0.877
		100% Inspection							
		0.45	0.54	0.63	0.72	0.77	0.81	0.86	0.90

4.0 Monte Carlo Simulation Analysis

To supplement the analytical results, it was desirable to evaluate the performance of the sampling plans when the assumption of defect-clustering does not hold. This was accomplished by application of Monte Carlo simulation techniques. A computer program was developed that simulates 100% inspection and various sampling plans of interest.

4.1 Flaw Distributions

A steam generator with the same number of tubes as a Westinghouse Model 51 generator (i.e., 3,388) was assumed, and twelve different tube maps were considered. Assuming one flaw per tube, Table 4.1 gives a brief description of the flaw distributions used in this work. As shown in Table 4.1, each flaw distribution has a specified number of flaws in each percent through-wall category. Tube maps 20 and 21 were provided by EPRI and represent field ISI results for two specific plants with Westinghouse Model 51 and Model 44 steam generators, respectively. The coordinates of the degraded and defective tubes for map 21 were set into the Westinghouse Model 51 geometry. The difference in geometries is slight - 46 rows and 94 columns for the Model 51 generator, and 45 rows and 92 columns for the Model 44 generator.

Figures 4.1 to 4.11 show symbol-coded tube maps that illustrate the flaw distributions represented by the numbers in Table 4.1. The Blank map is not illustrated. In Figures 4.1 to 4.11, each symbol represents a flaw size category (or interval). Rather than assigning the "midpoint" or "average" flaw size to each tube in a particular size category, it was desirable that the flaws within each category represent a random sample from a continuous distribution of flaw sizes.

To accomplish this, it is assumed that the flaw sizes within each category are approximately uniformly distributed. Then, for each tube in a particular flaw size category, true flaw size X was randomly generated from a uniform (or rectangular) distribution with endpoints equal to the upper and lower limits of the flaw size category. All tubes without symbols have no flaws.

Table 4.1. Tube Maps (Flaw Distributions) for Simulation Analyses

Map	< 20%	20 - 49%	50 - 75%	75 - 100%	Distribution of Flaws
1	15	5	5	5	Small Isolated Clusters
1A	0	5	5	5	Small Isolated Clusters
3	15	5	5	5	Single Cluster
6	90	40	40	10	Isolated Clusters
6A	0	40	40	10	Isolated Clusters
8	92	38	40	10	Single Large Cluster
8A	0	38	40	10	Single Large Cluster
13	120	232	175	116	Predicted Surry
13A	0	232	175	116	Modified Predicted Surry
20	0	0	4	12	Isolated Defective Tubes
21	0	0	1	3	Isolated Defective Tubes
B	0	0	0	0	Blank (No Degradation)

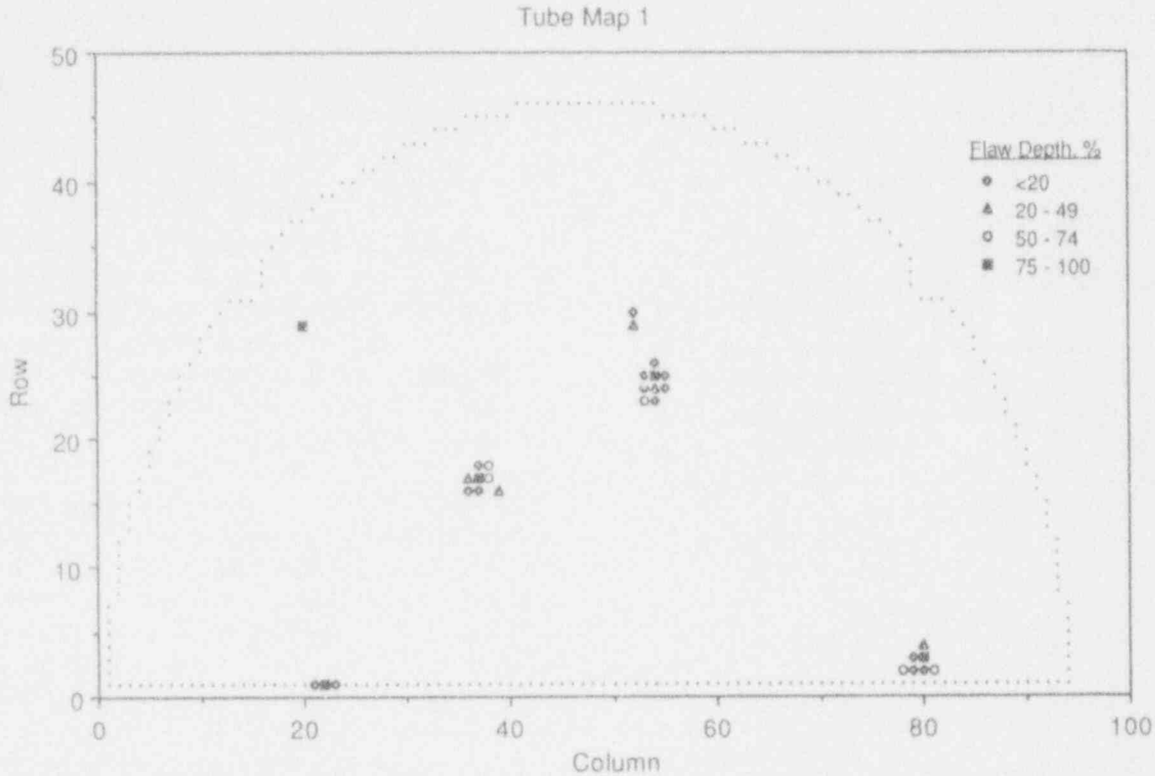

Figure 4.1. Monte Carlo Simulation Tube Map 1

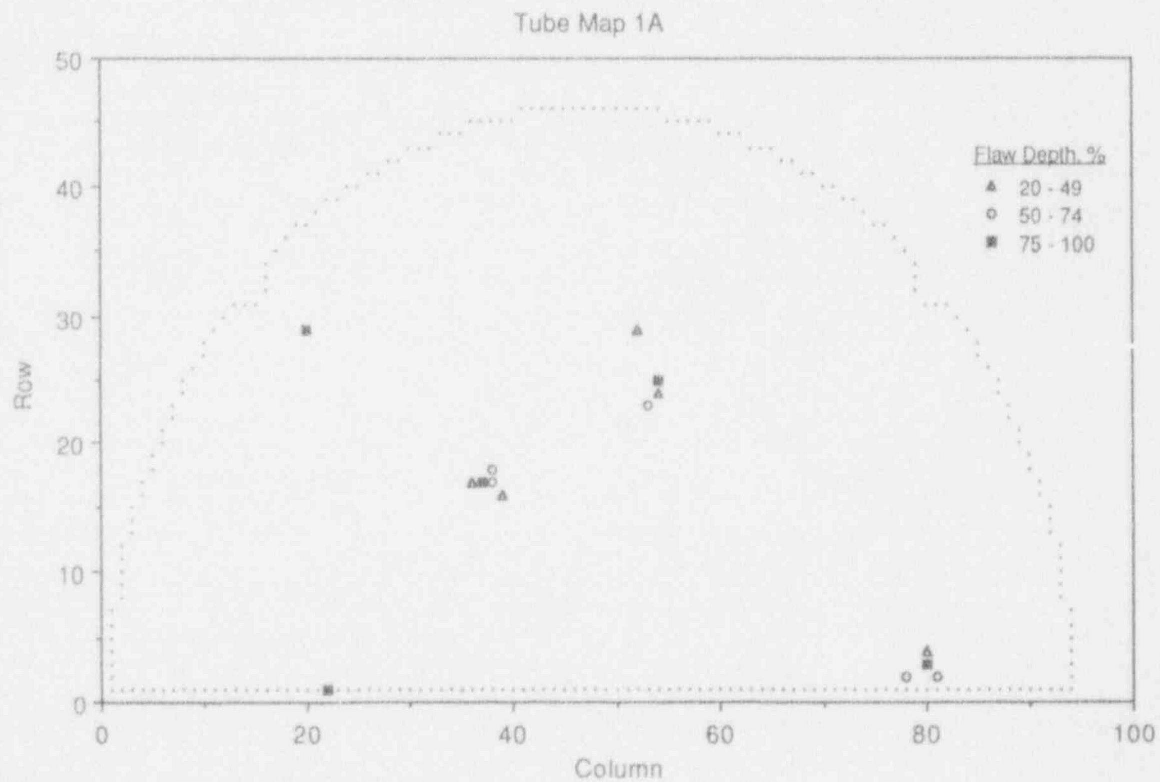

Figure 4.2. Monte Carlo Simulation Tube Map 1A

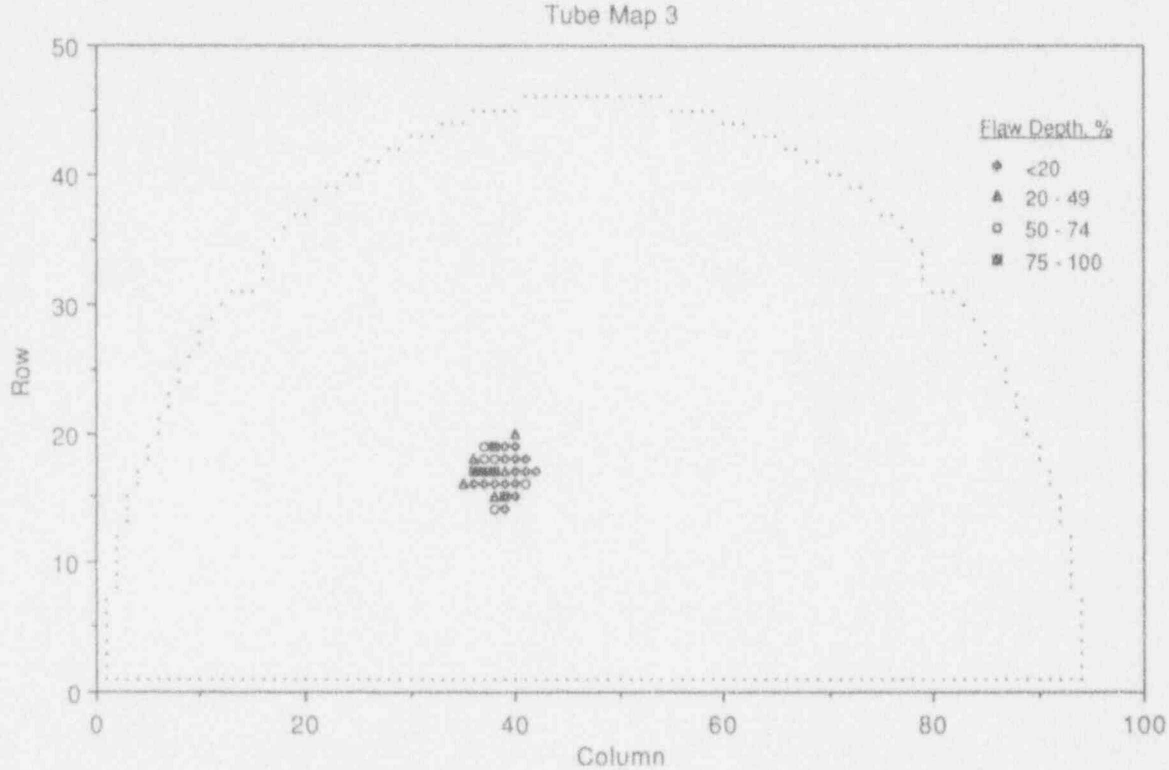

Figure 4.3. Monte Carlo Simulation Tube Map 3

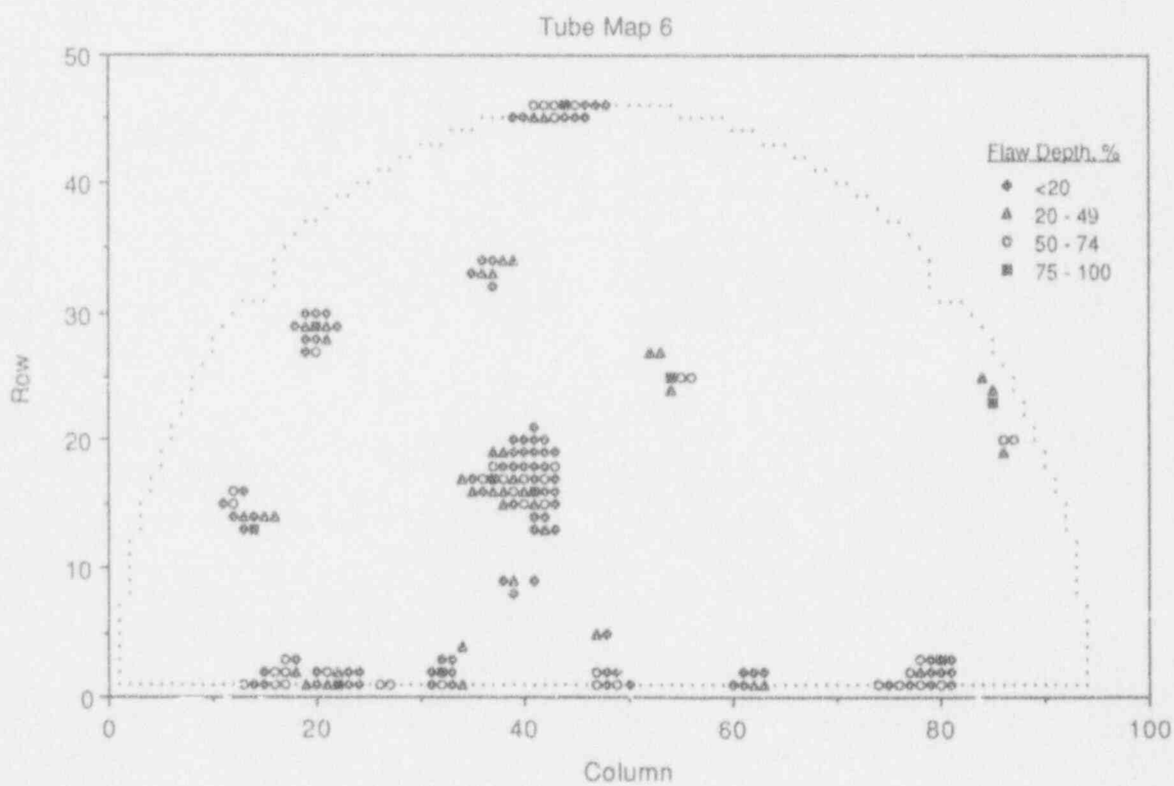

Figure 4.4. Monte Carlo Simulation Tube Map 6

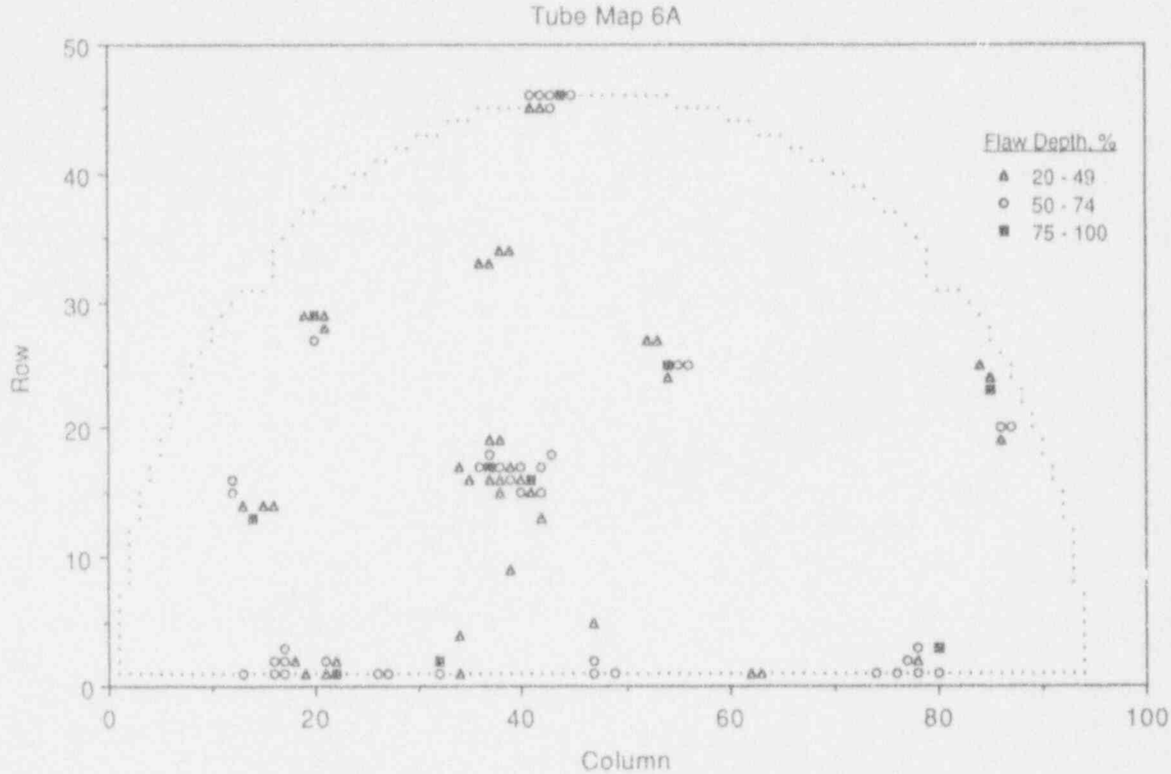

Figure 4.5. Monte Carlo Simulation Tube Map 6A

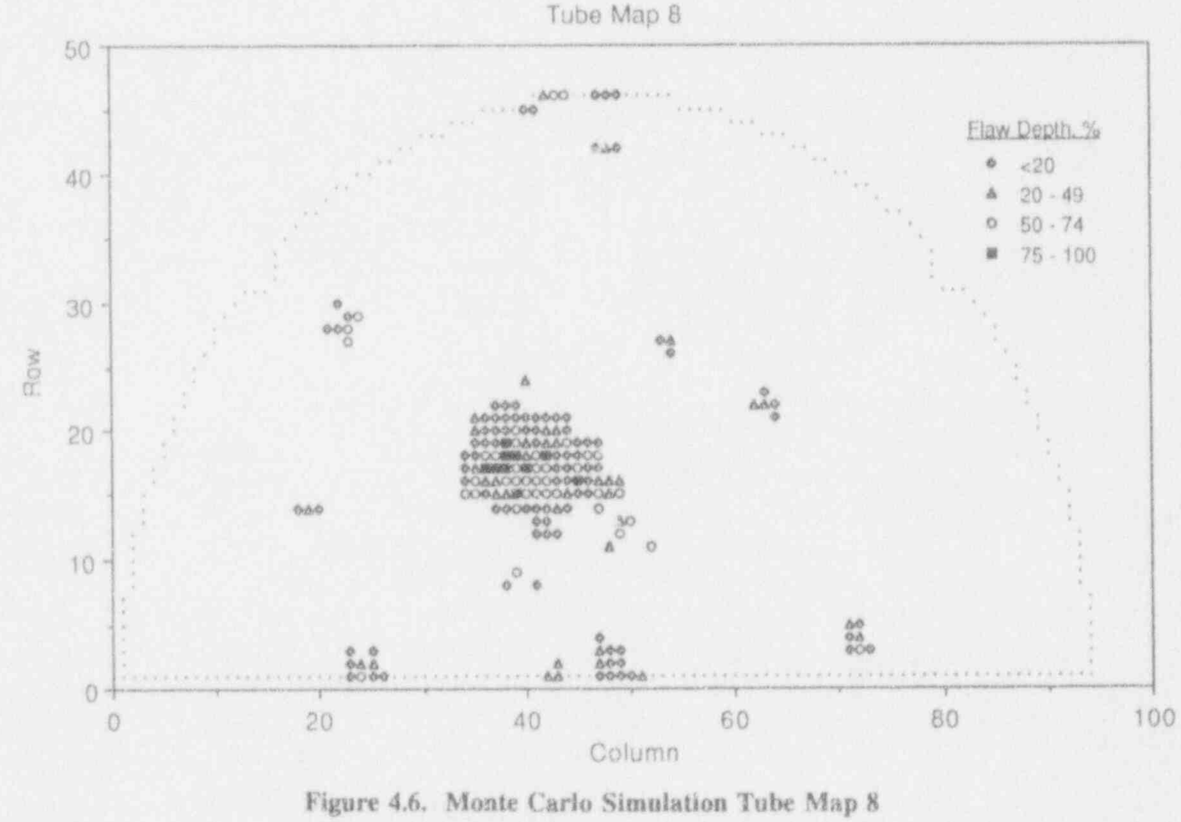

Figure 4.6. Monte Carlo Simulation Tube Map 8

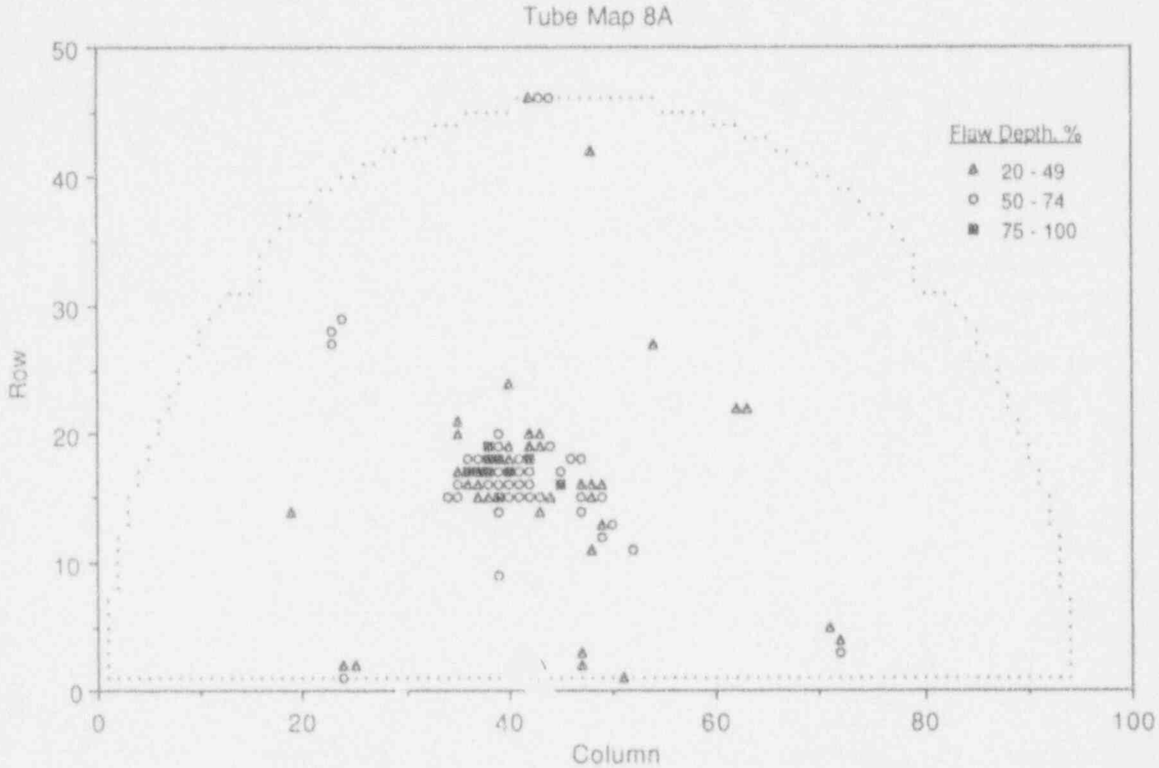

Figure 4.7. Monte Carlo Simulation Tube Map 8A

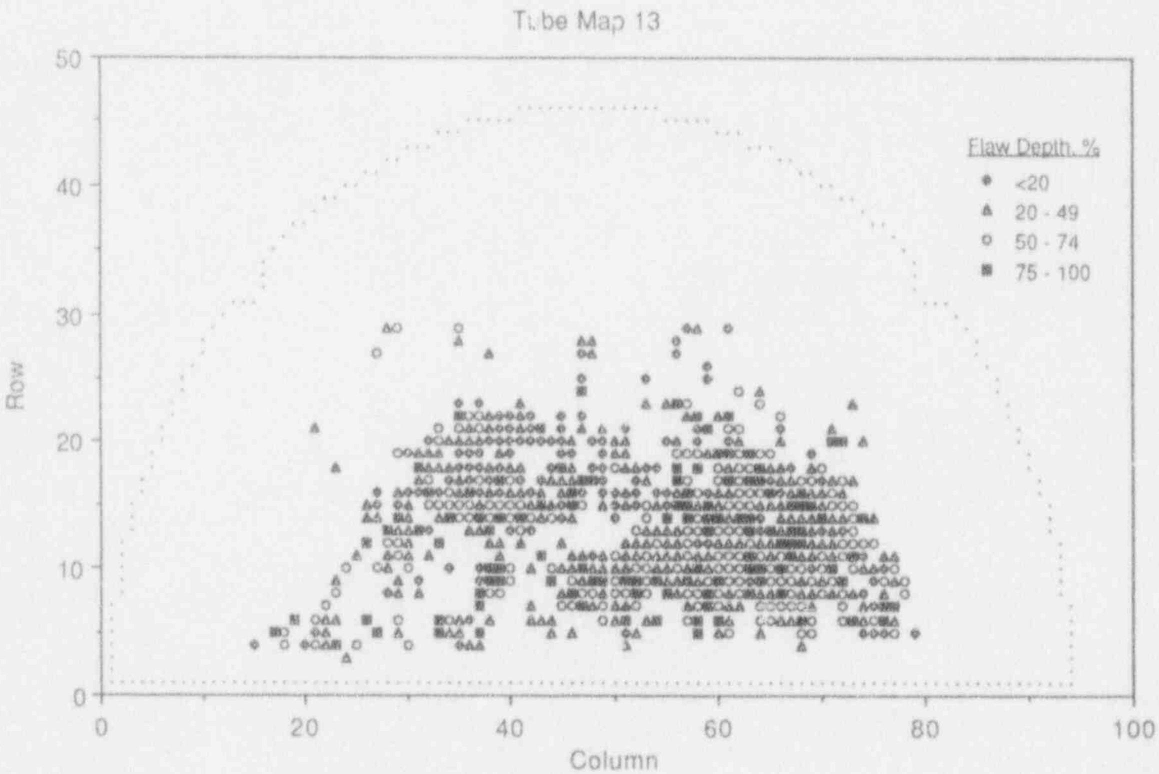

Figure 4.8. Monte Carlo Simulation Tube Map 13

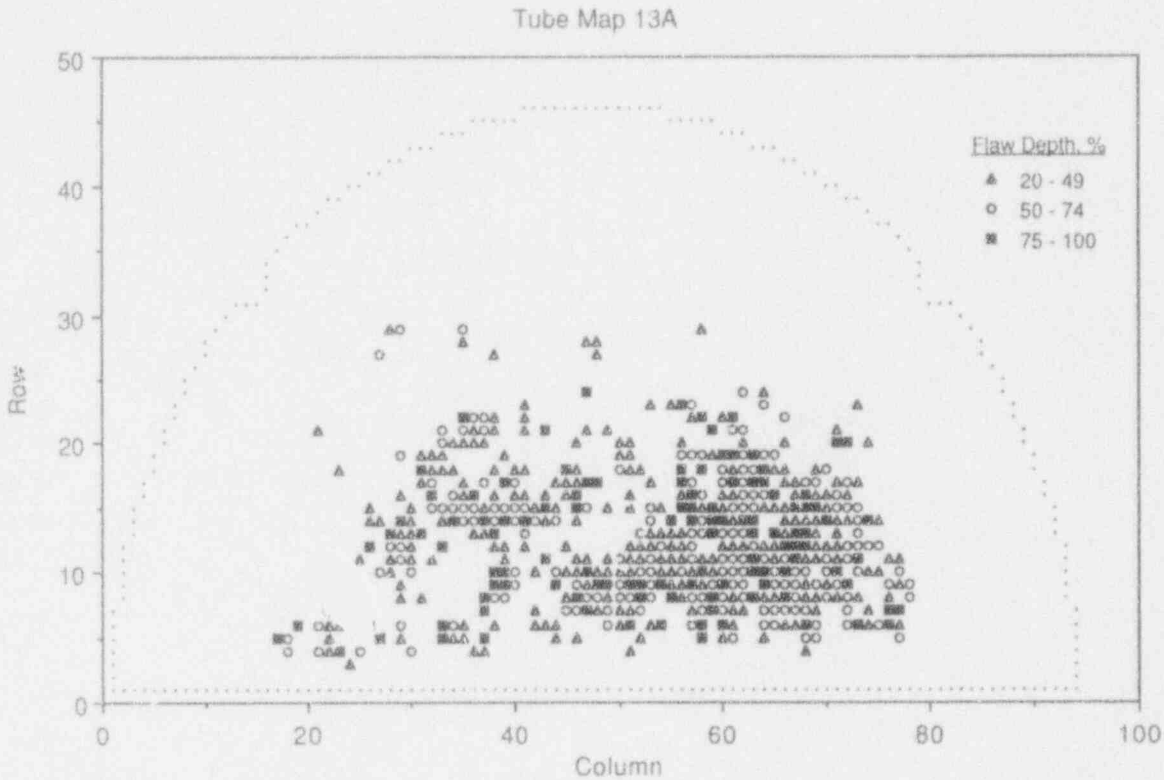

Figure 4.9. Monte Carlo Simulation Tube Map 13A

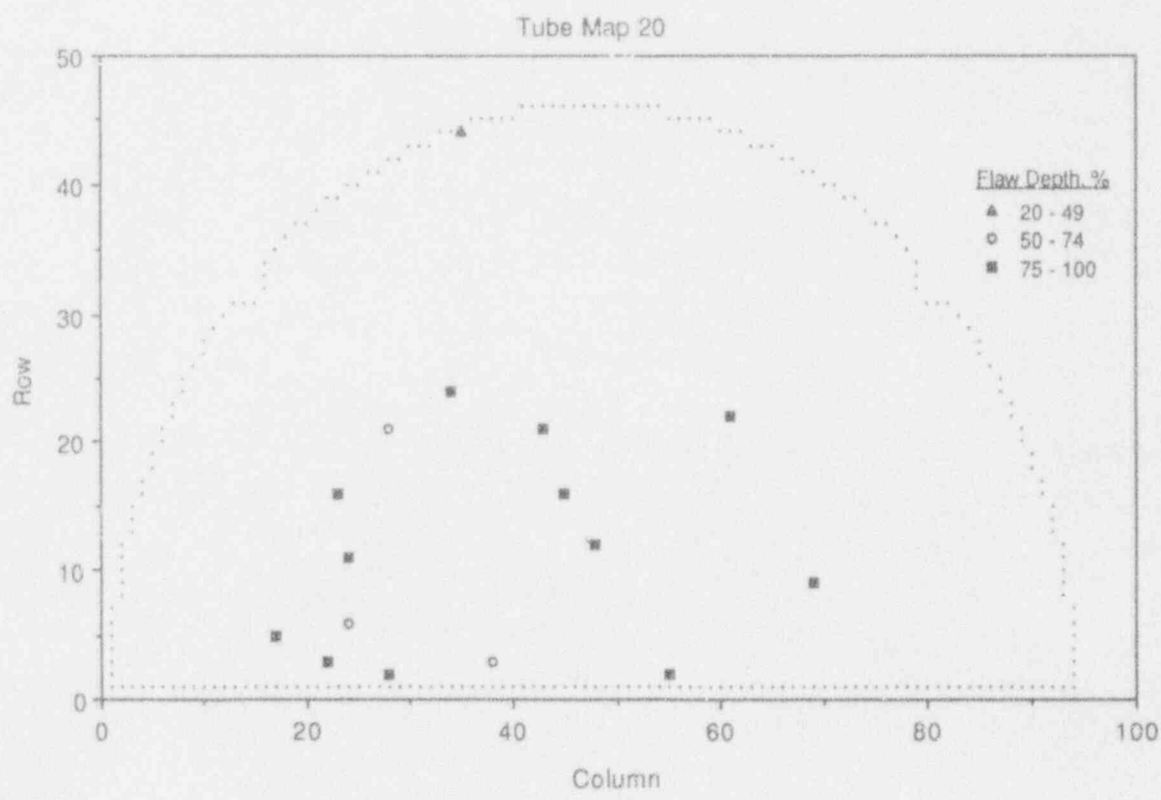

Figure 4.10. Monte Carlo Simulation Tube Map 20

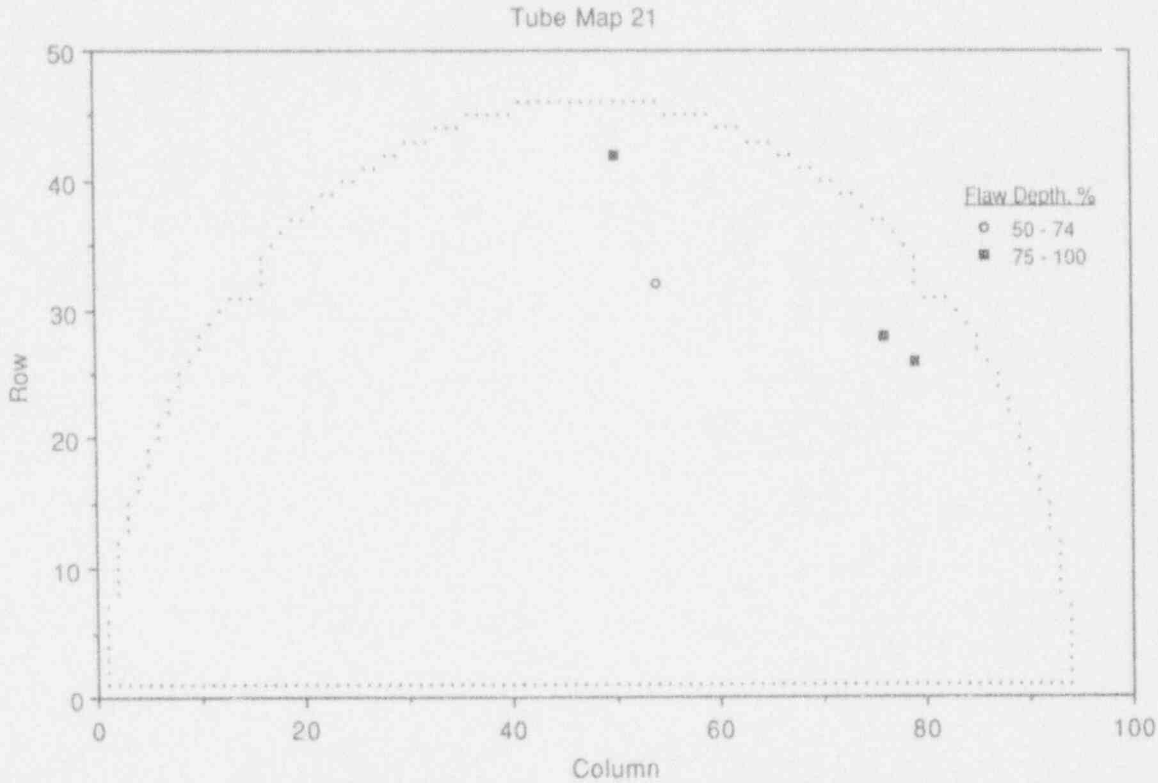

Figure 4.11. Monte Carlo Simulation Tube Map 21

It should be noted that the flaw distributions were chosen for the purpose of evaluating and comparing the performance of the sampling plans under various degrees of clustering. These distributions are not necessarily realistic, and they are not intended to represent any particular operating steam generators; any similarities are coincidental.

4.2 Probability of Detection and ET Sizing Models

As shown in the analytical evaluation, the effectiveness of a sampling plan depends on the POD, sizing capability, and plugging limit. Thus, to determine the outcome of a tube inspection, it was necessary to input: 1) a POD model that expresses POD as a function of true flaw size X, 2) an ET sizing model that expresses the expected (or mean) ET size as a function of true flaw size X and also provides the standard deviation of individual ET values about the mean value, and 3) an ET plugging limit such that a tube with an ET reading that exceeds the plugging limit will be plugged or repaired. It was of interest to study how changes in any or all of these factors would affect the performance of each sampling plan. To accomplish this, several different POD curves were considered. Figures 4.12 to 4.14 show the POD curves utilized.

Each POD curve defines a POD value for any true flaw size from $X = 0\%$ to $X = 100\%$ through-wall. The POD curves 1 and 2 in Figure 4.12 were chosen to represent lower (curve 1) and upper (curve 2) bounds on the POD estimates obtained from the Surry inspection data prior to the final POD analysis presented in the Task 13 Report (Bradley et al. 1988). Note, however, that curves 1 and 2 do not include a false call probability; that is, in Figure 4.12, both curves have POD = 0 when the true flaw depth is $X = 0\%$. Although this zero false call probability is not realistic, false calls can only improve the effectiveness of sampling plans. Thus, an evaluation of the effectiveness with zero false call probability will tend to be conservative.

The POD curves 4 and 5 in Figure 4.13 are a refinement of curves 1 and 2 based on later POD estimates. Note curve 4 is a somewhat more optimistic estimate of

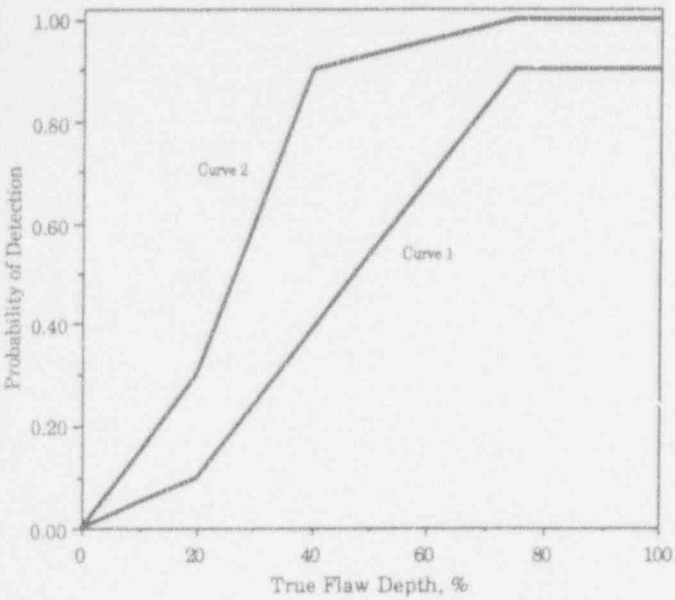

Figure 4.12. Monte Carlo Simulation POD Curves 1 and 2

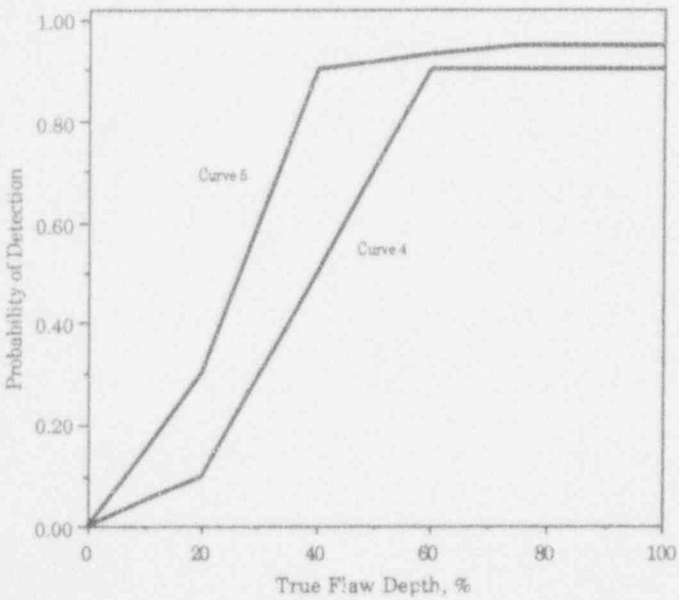

Figure 4.13. Monte Carlo Simulation POD Curves 4 and 5

the lower bound POD performance than curve 1, and curve 5 is a less optimistic upper bound on POD than curve 2. Note also that curves 4 and 5 have a zero false call probability; that is POD = 0 at X = 0%.

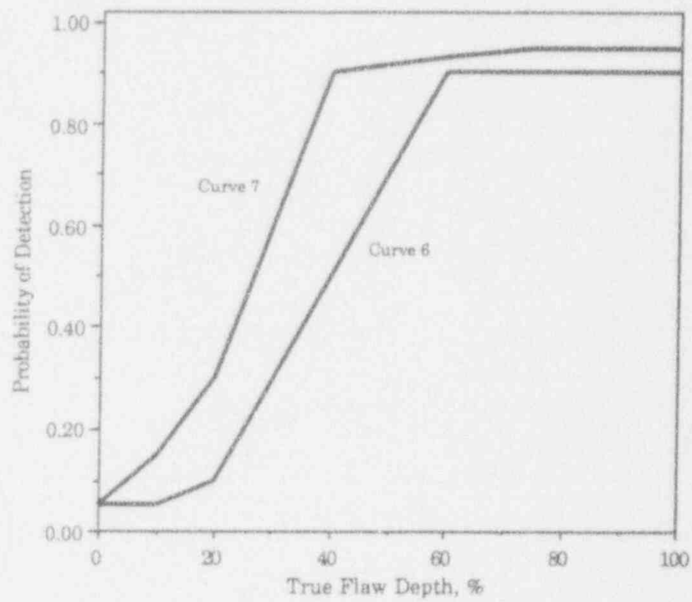

Figure 4.14. Monte Carlo Simulation POD Curves 6 and 7

The POD curves 6 and 7 in Figure 4.14 are simply curves 4 and 5 modified to include a 0.05 false call probability. Thus, a comparison of results based on curves 6 and 7 with curves 4 and 5 should reveal how false calls affect the performance of the sampling plans. Also, simulations performed on the blank tube map (no flaws present) and either curve 6 or 7 should provide additional information on the impact of false calls on increased inspection and plugging of tubes.

To study the effect of sizing capability on the effectiveness of the sampling plans, two ET sizing models were considered. Model 1 in Table 4.2 is intended to represent typical sizing capability of SGGP teams. Specifically, the parameters a and b were estimated by averaging the values of a and b (see Equation 2.1) for Teams A, B, C, D, and X. The standard deviation (SD), was estimated by first averaging the Var(e) values for these teams and then taking the square root of the average. Model 2 in Table 4.2 is the fitted model for the best performing SGGP team and is intended to represent an improved level of sizing performance.

4.3 Sampling Plans and Second Stage Inspection

There were 17 sampling plans considered in this study. A sampling plan consisted of type of plan (systematic or

Table 4.2. ET Sizing Models Used in Monte Carlo Simulations

Model	Equation	SD	Description
1	$14.5 + 0.46(X)$	16	Typical SGGP Team
2	$12.6 + 0.68(X)$	10	Best Sizing Performance

Table 4.3. Sampling/Inspection Plans Investigated

Type	Initial % of Total	Expansion Rule	Description
Systematic	20	Local 0 Local 2 Global 2	Every fifth tube inspected on grid
	33.3	Local 0 Local 2 Global 2	Every third tube inspected on grid
	40	Local 0 Local 2 Global 2	Two of every five tubes inspected on grid
Random	3	C1, C2, C3	Standard Technical Specifications (STS)
	20	Local 0 Local 2	
	33.3	Local 0 Local 2	
	40	Local 0 Local 2	
NA	100	NA	100% inspection case

random), initial percent of the total tube population sampled, and the second-stage expansion rule. The 17sampling plans are given in Table 4.3. Note that four different types of second-stage expansion rules were evaluated in this study.

The local expansion rule (LER) denoted as Local 0 or Local 2 was used in most of the simulations and triggered second-stage inspection when a tube with a positive ET indication was observed. For the Local 0 rule, any tube with an ET indication > 0% triggered additional inspection in the region immediately surrounding the suspect tube until a two-tube wide "buffer zone" was observed, which was composed of tubes with no ET indications and completely surrounds the tube(s) with ET indications > 0%. For the Local 2 expansion rule, second-stage inspection analogous to Local 0 was triggered only when an ET indication > 20% was observed.

The global expansion rule (GER) was significantly different than the local expansion rules described above.

It triggered second-stage inspection when 1) one or more tubes from the initial sample was classified as defective (i.e., ET indication ≥ 40%), or 2) 5% or more of the initial sample of tubes was classified as degraded (i.e., ET indication > 20% but < 40%). The extent of second-stage inspection mandated by the GER was 100% of the "region" of interest. It should be noted that the GER is similar to, but not the same as, the second-stage expansion rules presented in the report EPRI NP-6201. In this work we have assumed that, if the results of the initial sample triggered second-stage inspection, then all remaining tubes in the steam generator were inspected full-length. This is not the recommendation given in EPRI NP-6201. The EPRI NP-6201 expansion rules allow for limited examination at the second-stage depending on the type of steam generator, the tube damage mechanism, and plant history. Since determination of flaw type is largely based on ET indication location within the tube bundle and prior experience, there is a potential that an ET indication may not be correctly classified and the inspection not expanded sufficiently. No attempt was made to model this potential unreliability in the inspection process. Therefore, the evaluations discussed in this report must be taken as an upper bound estimate of the sampling plans using the expansion rules given in EPRI NP-6201.

The last second-stage expansion rule considered was the Standard Technical Specification (STS) requirement. For the STS expansion rule, the level of second-stage inspection also depends on the number and severity of the flaws found during first-stage sampling. The inspection result categories are described in Table 4.4 and the different levels of inspection required for each result category are given in Table 4.5. Note that the criteria have been reduced to one steam generator. In the STS, the criteria affect all of the steam generators at a particular plant.

Table 4.4. Standard Technical Specification Requirement Inspection Result Categories

Category	Inspection Result
C1	Less than 5% inspected are degraded or none are defective
C2	Between 5% and 10% inspected are degraded or less than 1% are defective
C3	More than 10% inspected are degraded or more than 1% are defective

Table 4.5. Standard Technical Specification Requirement Second-Stage Inspection Criteria

Initial Inspection Result	Initial Action Required	Second Inspection Result	Second Action Required
C1	None	NA	NA
C2	Plug defective tubes. Inspect 6% more tubes.	C1	None
		C2	Plug defective tubes. Inspect 12% more tubes.
		C3	100% inspection
C3	100% inspection	NA	NA

Table 4.6. Monte Carlo Simulation Steps

Step	Description
1	Read tube map with true flaw sizes X.
2	Inspect tubes according to sampling plan.
3	Based on true flaw size and POD curve, assign probability of ET > 0, then randomly generate "detected" or "not detected" for each tube.
4	If ET > 0, use sizing model to generate "ET size" Y from a normal distribution with mean $a + bX$ and standard deviation SD. This provides the 100% inspection result.
5	If "ET size" Y > plugging limit (40%), plug tube.
6	Compare inspection results with expansion rule and perform second-stage inspection as needed.
7	Repeat Steps 2 through 6, 25 times and tabulate summary statistics. Shift grid as necessary for systematic sampling.*

*Sampling grid not shifted for simulations performed on tube maps 1, 3, 8, and 13.

4.4 Simulation Methodology

The simulation analysis strategy was to consider various combinations of flaw distribution, POD curve, and ET sizing model with each sampling plan. For a given combination of these parameters, 25 independent applications of all sampling plans were simulated. For each combination, the process outlined in Table 4.6 was followed. This process is classified as a Monte Carlo simulation because of the randomness introduced in steps 3 and 4 of Table 4.6. Consider, for example, a particular tube with true flaw size $X > 20\%$. Assume that this tube is included in the initial 20% systematic sample, in each of the 25 independent applications of the sampling plan, this tube has a chance of being detected in Step 3. However, it could be detected in some of the applications and not others.

In each of the 25 applications, the outcome of step 6 determines whether additional inspection is performed. Thus, the total number of tubes inspected can be expected to differ from application to application. In each of the 25 applications, the outcome of step 3 also determines whether or not the flaw sizing in step 4 is carried out. If step 4 results in detection (ET > 0%), then an ET flaw size is randomly generated from a normal distribution with mean and standard deviation defined by the sizing model. Thus each time a flaw is detected, a different ET size will be generated. The implication is that the outcome of step 5 for this tube can differ from application to application.

4.5 Simulation Results

The principal measure of sampling plan performance for detecting and plugging defective tubes was the sampling plan effectiveness. The sampling plan effectiveness was defined as the ratio of the mean number of defective tubes plugged to the total number of defective tubes in the tube map. The effectiveness parameter provided a means for comparing the plugging capability of various sampling plans across different tube maps. To determine the sampling plan efficiency, comparisons were made of the mean number of defective tubes plugged by a sampling plan to the mean number of defective tubes plugged using 100% inspection. These comparisons provided an assessment of how well a sampling plan performed relative to the best possible (100% inspection).

The complete output of all simulation results for all cases considered is too voluminous to include in this report. Thus, only a limited subset of the results for each tube map is presented in this section. The limited subset of results is summarized to provide a basis for the comparisons and evaluations of interest. Detailed summaries are included in Appendix A by tube map.

4.5.1 Effect of Inspection System Reliability

The simulation results provide valuable insights into the effect of inspection system reliability on the sampling plan effectiveness for detecting and plugging defective tubes. Figures 4.15 and 4.16 show plots giving the average difference (for all systematic sampling plans) in sampling plan effectiveness for various POD curve/sizing model combinations for eight tube maps. The differences in Figure 4.15 were calculated by subtracting the sampling plan effectiveness for POD curve 4/sizing model X from POD curve 5/sizing model X. These results show the effect of increasing POD performance at constant sizing reliability. Note that in most cases the sampling plan effectiveness increased with increasing POD performance. The average increase in sampling plan effectiveness across all tube maps was about 0.05 which corresponds to the difference in POD between curves 4 and 5 when $X \geq 75\%$.

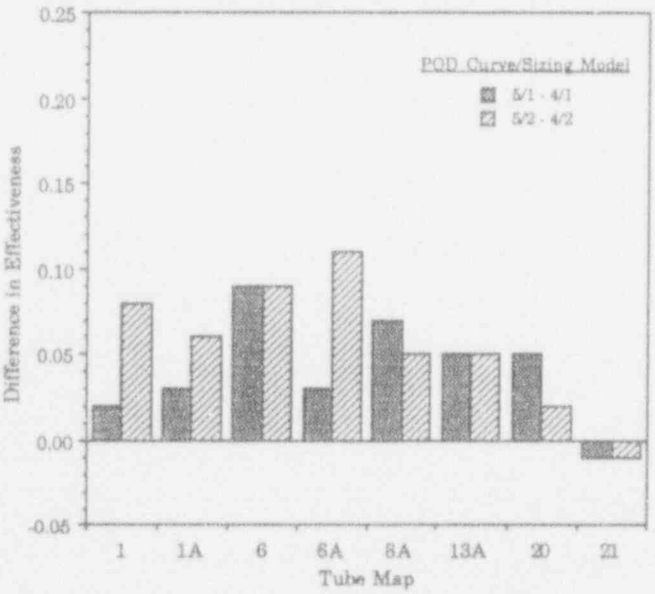

Figure 4.15. Effect of POD Performance on Sampling Plan Effectiveness

The results plotted in Figure 4.16 show the effect of improving sizing reliability at constant POD. The differences in Figure 4.16 were calculated by subtracting the sampling plan effectiveness for POD curve X/sizing model 1 from POD curve X/sizing model 2. Note that in all cases the sampling plan effectiveness increased with increasing flaw sizing performance. The average increase in sampling plan effectiveness across all tube maps was about 0.13, which roughly corresponds to the difference in PEL between sizing models 1 and 2 when $X \geq 75\%$. These results indicate that given a choice of improving sizing reliability from model 1 to model 2 versus the detection reliability from curve 4 to curve 5, then changing the sizing reliability would provide the biggest increase in inspection effectiveness.

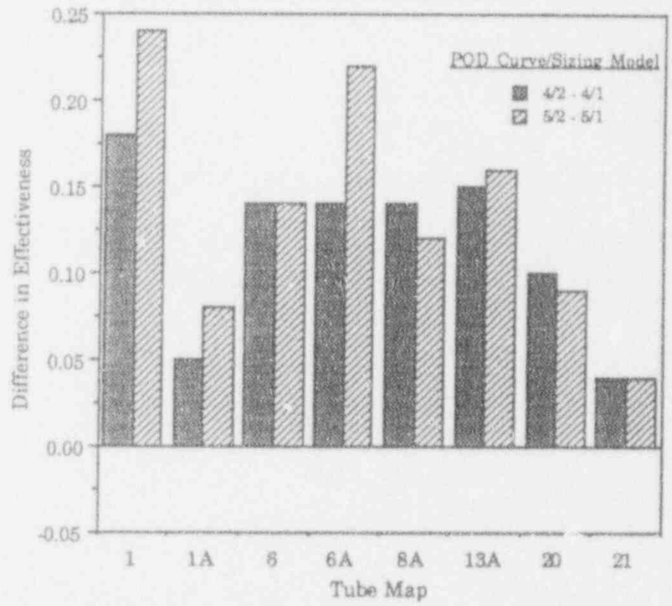

Figure 4.16. Effect of Sizing Performance on Sampling Plan Effectiveness

4.5.2 Systematic Versus Random Sampling

An objective of the Monte Carlo simulation work was to evaluate the difference in sampling plan effectiveness for different systematic and randomly selected initial sample sizes. Figure 4.17 shows a plot of the difference in systematic and random sampling plan effectiveness for the six tube maps for which these simulations were performed. The plot shows the differences broken down by initial sample size, either 20%, 33.3%, or 40%. If no bar is displayed for a particular tube map and initial sample size, then the difference between the systematic and random sample plans is zero for that combination. The results indicate that there is no statistically significant difference between systematic and randomly selected initial samples. As a consequence, the remainder of the discussion in this section is focussed on results obtained from the systematic sampling plans. Since the systematic and random sampling plans evaluated in this report gave nearly equivalent results, the conclusions reached apply to both.

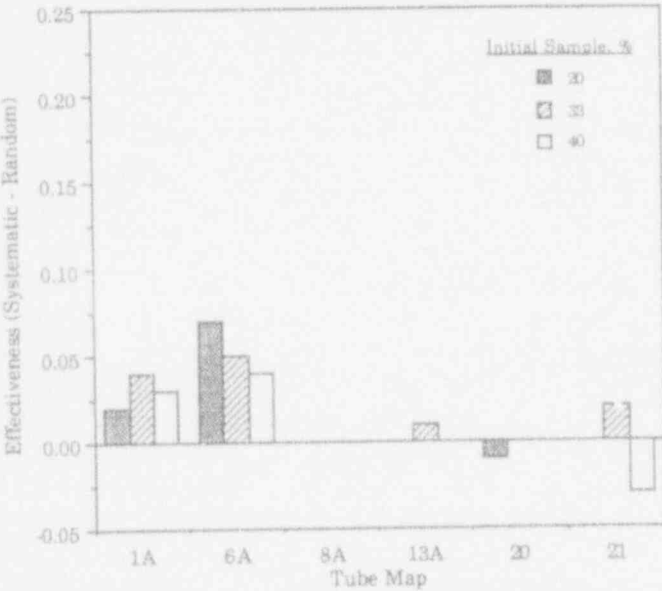

Figure 4.17. Effect of Systematic Versus Random Sampling on Sampling Plan Effectiveness

4.5.3 Effect of Degraded Tube Threshold

Several simulations were performed to evaluate the effect of the definition of a degraded tube. All of the sampling plans have expansion rules which trigger second-stage inspection when some number of tubes from the initial sample have been classified as degraded. Two definitions of a degraded tube were considered in this analysis. In one series of simulations a degraded tube was defined as any tube with an ET indication > 0% but less than 75%. Another set of simulations was performed in which a degraded tube was defined as any tube with an ET indication ≥ 20% but less than 75%. The 20% threshold was selected to reflect common field practice and the difficulty of detecting and sizing < 20% indications. Simulations were performed for six tube maps (1A, 6A, 8A, 13A, 20, and 21), four POD curve/sizing model combinations (4/1, 4/2, 5/1, and 5/2), three systematic sampling plans (20%, 33.3%, and 40%), and the LER to trigger second-stage inspection. Figure 4.18 shows a histogram of the sampling plan effectiveness for systematic sampling plans employing the 20% degraded tube definition minus systematic sampling plans employing the 0% degraded tube definition (i.e., SX2 - SX0). There was essentially no effect of the POD curve/sizing model combination observed, so the average for all four POD curve/sizing model combinations was used to construct Figure 4.18. It is clear from the results that the degraded tube definition did not effect inspection effectiveness significantly. In fact, for four tube maps (8A, 13A, 20, and 21) the average effectiveness difference was zero, and for the other tube maps the average difference was 0.02 or less. The lack of a degraded tube threshold effect is likely due to the specific tube flaw sizes considered for the six tube maps considered.

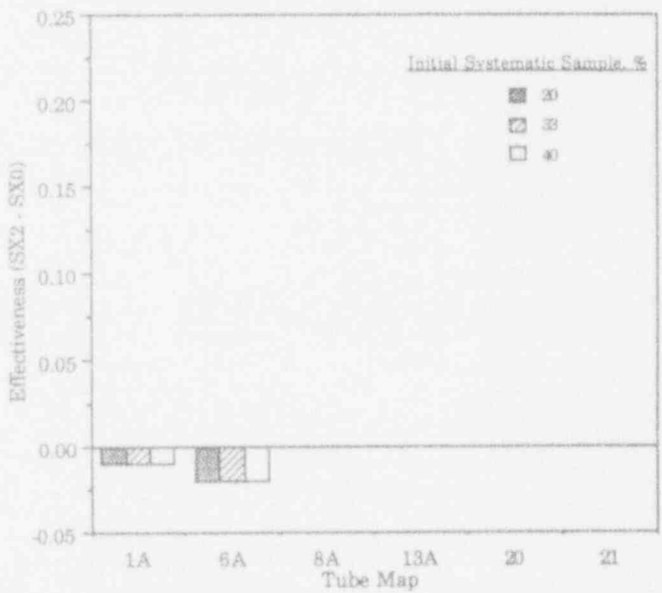

Figure 4.18. Effect of Degraded Tube Threshold on Sampling Plan Effectiveness

4.5.4 Effect of Initial Sample Size and Flaw Distribution

The effect of the initial sample size and flaw distribution on sampling plan effectiveness is shown in Figures 4.19 and 4.20. Simulations were performed for six tube maps (1A, 6A, 8A, 13A, 20, 21), four POD curve/sizing model combinations (4/1, 4/2, 5/1, 5/2), and three systematic sampling plans. The LER was used as the criterion to trigger second-stage inspection for all sampling plans considered. In addition, the STS was also simulated.

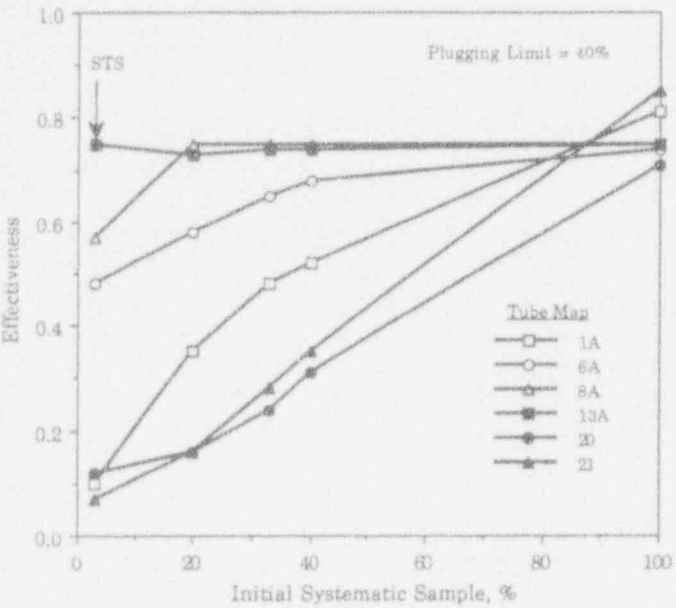

Figure 4.19. Sampling Plan Effectiveness Versus Initial Systematic Sample Size for POD Curve 4 and Sizing Model 1

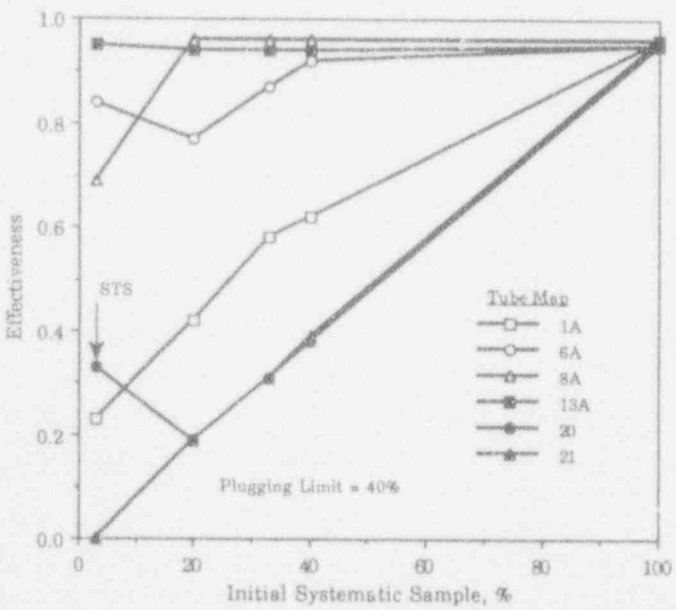

Figure 4.20. Sampling Plan Effectiveness Versus Initial Systematic Sample Size for POD Curve 5 and Sizing Model 2

Only the results for the worst and best combination of POD curve and sizing model are presented. Figures 4.19 and 4.20 display results for three tube maps in which the flaws are isolated or nearly isolated. In other words, the flaw distributions do not exhibit a significant degree of clustering. The simulation results show that in two out of three cases the sampling plan effectiveness was approximately linearly related to the initial sample size. It is significant to note that the STS sampling plan performed the worst in nearly all cases and resulted in the highest mean number of tubes inspected per defective plugged. It is clear from the results for tube maps 20 and 21 that when flaws are completely isolated that the best strategy for steam generator inspection is 100% inspection since this is the most effective for identifying defective tubes and gives the lowest number of tubes inspected per defective plugged.

In three tube maps, the flaws are clustered or occur in groups of neighboring tubes. In general, all sampling plans are equally effective (except for the STS) for detecting and plugging defective tubes when the defective tubes are surrounded by large numbers of degraded tubes. That is, enough inspection was triggered by each sampling plan to result in a thorough inspection of the region containing the defective tubes. The effectiveness of the sampling plan in this case depends on the POD curve and sizing model combination, rather than the initial sample size.

For all the systematic sampling plans, if map 13 and map 13A results are excluded, the total number of tubes inspected increased by ≤ 10% of the total number of tubes in the generator. Only when degradation was copious did the systematic sampling plans expand more than 10% beyond the initial sample. It is significant to note that even in these two cases (map 13 and map 13A), the level of inspection for all the sampling plans was considerably less than 100% but still achieved nearly the same effectiveness as 100% inspection.

For the STS, depending on the amount and distribution of tube degradation, the number of tubes inspected for each simulation run was highly erratic, either 3% or 100%. For tube maps with isolated defectives, only the minimum 3% inspection was performed for nearly all 25 runs. For tube maps with large numbers of defectives or more clustering, then the initial 3% inspection often expanded to 100% inspection. It is important to observe that in several instances of intermediate clustering, the STS resulted in significantly more tubes inspected, but did not yield as high an effectiveness as the other sampling plans investigated.

4.5.5 Local Versus Global Expansion Rules

The effectiveness of the GER and LER are compared in Figures 4.21 and 4.22. The results show that sampling plans using the GER tend to be most effective for isolated degradation distributions (maps 1, 20, 21). For flaw distributions exhibiting more clustering (map 6), sampling plans using the GER were more effective than plans using the LER, but the LER plans gave similar performance. This was especially true for the best POD curve/sizing model combination. It is also observed that for a more clustered flaw distribution, the 40%/LER sampling plan gave performance very close to 100% inspection, but with far fewer tubes inspected.

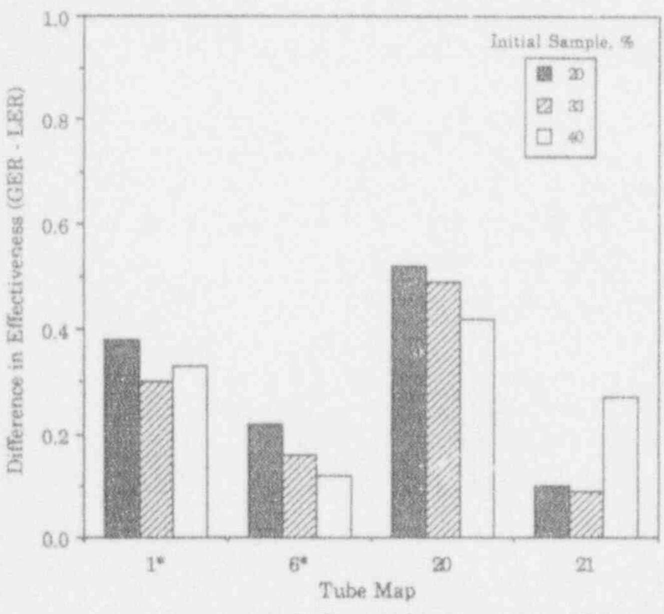

Figure 4.21. Difference in Sampling Plan Effectiveness (Global Expansion Rule Minus Local Expansion Rule) With POD Curve 4 and Sizing Model 1

The simulation results also indicated that sampling plans using the GER resulted in 100% inspection in almost all cases (see Appendix A). Only for cases of sparse, isolated degradation (map 21) did the plan inspect significantly less than 100% of the steam generator. It is important to note that in these simulations

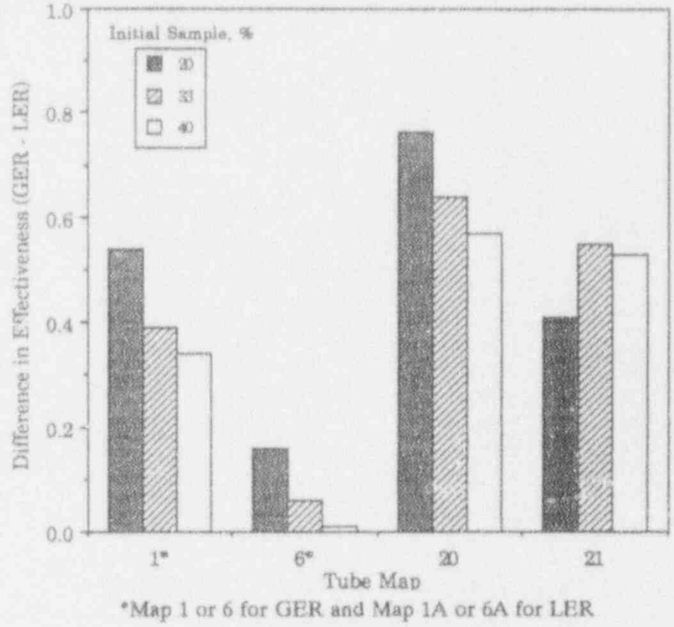

Figure 4.22. Difference in Sampling Plan Effectiveness (Global Expansion Rule Minus Local Expansion Rule) With POD Curve 5 and Sizing Model 2

we have assumed that 100% inspection of a "region" constitutes the entire steam generator tube bundle. If this is not the case, the effectiveness of the GER may be less than indicated by these results since some defective tubes may go uninspected.

4.5.6 Effect of False Calls

The final issue studied in the simulation analysis is the impact of a non-zero false call probability on the total number of tubes inspected using systematic sampling with the LER, and whether the additional inspections triggered by false calls enhances the effectiveness of the sampling plans. The results plotted in Figure 4.23 were generated to help determine whether the additional inspection triggered by the false calls significantly enhances the effectiveness of the systematic sampling plans. The discussion of POD curves 4, 5, 6, and 7 (see Figures 4.13 and 4.14) indicates that curves 6 and 7 are modifications of curves 4 and 5 to include a 0.05 false call probability. Therefore, comparing curve 6 results with the curve 4 results, and the curve 7 results with curve 5 results, provides information on the impact of the 0.05 false call probability on the number of tubes inspected and the number of defective tubes plugged.

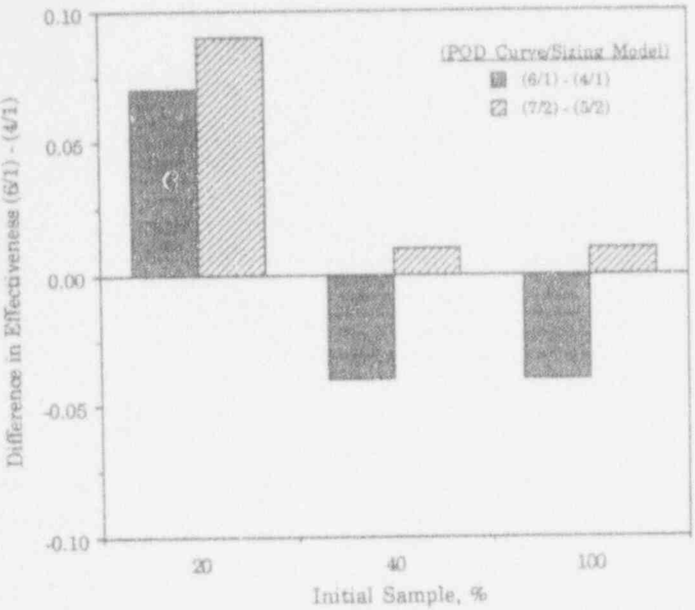

Figure 4.23. Effect False Calls on Sampling Plan Effectiveness for Tube Map 6

Note first that with 100% inspection, false calls will not affect the number of defective tubes plugged. Therefore, observed differences in the 100% inspection results reflects the nonrepeatability due to randomness. Using this as a basis for judging the significance of observed differences in the results, there appears to be some improvement for the 20% sampling plan, but not for the 40% plan, indicating that the 20% sampling plan is not as efficient as the 40% plan in cases of clustered degradation. The differences in the number of tubes inspected is consistent with the conclusions discussed in connection with Figure 4.24. The results displayed in Figure 4.24 were generated to estimate the effect of a 0.05 false call probability on the total number of tubes inspected. A blank map was used so that increased inspection due to detection of actual flaws would not cloud the issue. Note that the average number of tubes inspected with the 20% systematic sampling plan ranges from 39% to 42% of the 3,388 tubes in the generator. That is, the 0.05 false call probability has triggered inspection of an additional 19% to 22% of the tubes. The average number of tubes inspected with the 40% systematic sampling plan ranges from 64% to 66%; the 0.05 false call probability has triggered inspection of an additional 24% to 26% of the tubes in the generator. Thus, a non-zero false call probability does significantly increase the number of tubes inspected with the systematic sampling plans. However, a 0.05 false call probability does not cause either of the systematic sampling plans to increase to 100% inspection.

Also displayed in Figure 4.24 are the average number of tubes with ET indications that exceeded the plugging limit. Note that sizing model 2, representing better sizing capability, results in fewer blank tubes being plugged.

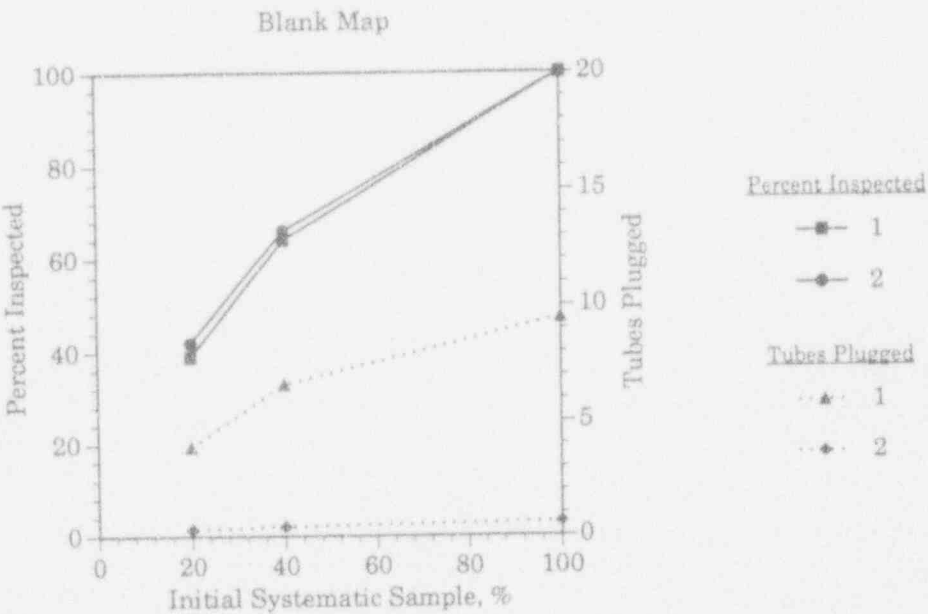

Figure 4.24. Effect of False Calls on the Total Number of Tubes Inspected for a Steam Generator With no Degradation (Blank Map)

5.0 Conclusions

The goal of this research was to evaluate and compare a number of different sampling plans for their effectiveness in detecting and plugging defective tubes. Analytical evaluation and Monte Carlo simulation techniques were the methods used to compare sampling plan performance. To test the performance of candidate sampling plans under a variety of conditions, ranges of inspection system reliability were considered, along with different distributions of tube degradation. Results from the ET reliability studies performed with the retired-from-service Surry 2A steam generator were utilized to guide the selection of appropriate POD and PEL ranges for use in this analysis. Different distributions of tube degradation were selected to span a range of conditions from a low level of degraded tube clustering (essentially isolated defective tubes) up to a high level of degraded tube clustering such as represented by the Surry steam generator. In this work, a defective tube was defined as one with ≥ 75% through-wall degradation at the time of ISI. This definition was based on tube integrity data developed during earlier phases of the program.

It is useful to consider how well the sampling plans performed relative to 100% inspection. It is clear from this work that the most effective strategy for detecting and plugging defective tubes is 100% inspection. The effectiveness of all sampling plans relative to 100% inspection was found to depend on the number and distribution of degraded tubes in a particular tube map. For some degradation distributions, a 40% systematic sampling plan was almost as effective as 100% inspection.

The analytical evaluation of sampling plans was based on the assumptions stated in Section 3 (particularly the clustering assumption) and the ranges of POD and PEL values used in the analysis. The analytical results for 100% inspection do not, however, depend on the cluster assumption.

The results of the analytical evaluation demonstrated that if the assumption of small isolated clusters holds and if the POD for degraded but not defective tubes is at least 0.7, then of the two-stage sampling plans considered, the 40%/LER systematic scheme was nearly as effective as 100% inspection for detecting and plugging defective tubes. This is true for any PEL value. However, the 20%/LER systematic scheme was significantly inferior to both 100% inspection and the 40%/LER systematic scheme.

In implementing a two-stage systematic scheme, the sampling grid should be "shifted" at each ISI so that every tube in a generator will eventually be inspected. For example, with the 40%/LER systematic sampling plan every tube in a generator would be inspected at least once during the course of three consecutive ISIs and at least twice during the course of five consecutive ISIs.

The results of the Monte Carlo simulation analysis support the conclusions reached from the analytical evaluation and provide some valuable additional insights. The results indicate that there is a distinct difference between the extremes of inspection system reliability considered. For POD curve 5 and flaw sizing model 2, the overall inspection effectiveness was about 95%. For POD curve 4 and flaw sizing model 1, the overall inspection effectiveness was only 75%. Improving the sizing reliability from sizing model 1 to sizing model 2 results in improved effectiveness of all sampling plans. Improving the POD enhances the effectiveness of all sampling plans. There was a strong indication that the effects due to sizing model differences were much larger than changes in detection reliability. This means that if one were given a choice of improving sizing reliability from model 1 to model 2 versus detection reliability from POD curve 4 to POD curve 5, then improving the sizing reliability would result in the largest increase in overall ISI effectiveness. However, it should be emphasized that attaining a high detection reliability is still a desirable situation since a flaw cannot be sized or otherwise dispositioned until it is detected.

Comparing random and systematic sampling plans, there was no statistically significant difference between systematic and randomly selected initial samples.

For a given sampling plan, the effectiveness was unchanged if degraded tubes were considered to be any tube with an indication > 0% through-wall as opposed to defining a degraded tube as one with an ET indication ≥ 20% through-wall. The lack of a degraded tube threshold effect is likely due to the low POD for flaws ≤ 20% through-wall and the small numbers of these flaws included in the various tube maps.

Sampling plan effectiveness was found to depend significantly on the initial sample size and on the distribution of tube degradation. All sampling plans were equally effective at detecting and plugging defective tubes when the defective tubes were surrounded by large numbers of degraded tubes (except the STS). When a moderate degree of clustering exists, the most effective sampling strategy is the 40% systematic plan using the LER expansion rule. The 40%/LER sampling plan was almost as effective as 100% inspection when the defective tubes are surrounded by some degraded and defective tubes, and substantially less than 100% of the tubes were inspected to achieve this high level of effectiveness.

When the defective tubes are isolated and not in close proximity to degraded tubes, then the most effective strategy is 100% inspection. For the distributions of tube degradation considered, the effectiveness of systematic/LER sampling plans was linearly related to the initial sample size. As a general rule, the effectiveness of such plans was slightly less than the initial sample size. In other words, the effectiveness of the 40%/LER sampling plan was approximately 0.40 when the best POD curve/ET sizing model were assumed. On the other hand, the effectiveness of systematic/GER sampling plans was better than the systematic/LER sampling plans for the isolated degradation cases. This was true even when the initial sample size was only 20%. The better performance of the systematic/GER sampling plans was due to triggering of 100% inspection in almost all cases.

The STS plan did not perform as well as the other plans in general. The degree of clustering was not as important as the number of defective tubes present in the tube map. For the clustered defective tube maps using POD curve 5 and sizing model 2, the STS was only 72% and 88% as effective as 100% inspection. For the isolated defective tube map using POD curve 4 and sizing model 1, the STS was between 0% and 36% as effective as 100% inspection.

Comparing the GER sampling plan with the LER expansion rule showed that the GER expansion rule was the most effective for random, isolated flaw distributions (maps 1, 20, 21). For a degradation distribution exhibiting more clustering (map 6), the GER was more effective than the LER plan, but the LER gave similar performance at lower numbers of tubes inspected. It is also concluded that for many of the scenarios investigated, the GER sampling plan is equivalent to 100% inspection. This is true for any scenario involving tube maps 6 and 20. These tube maps contain more flawed tubes than maps 1 and 21, so this behavior is reasonable. We would want the sampling plan to expand substantially when the steam generator contains many flaws. It should be noted the GER was similar to but not the same as the expansion rules recommended in EPRI-NP-6201. For this work, the GER was taken as expansion of the inspection to all steam generator tubes over their entire length, as opposed to 100% inspection of a "region" as described in NP-6201. Thus, the present results are an upper bound estimate of the NP-6201 sample plan effectiveness.

The final issue studied in the simulation analysis is the impact of a 0.05 false call probability on the total number of tubes inspected, and whether the additional inspections triggered by false calls enhance the effectiveness of the two-stage sampling plans. For two-stage sampling plans, the resulting false calls triggered inspection of an additional 19% to 26% of the 3,388 tubes in the generator. However, a 0.05 false call probability did not cause any of the sampling plans to increase to 100% inspection. Also, it appears that the false calls improve the effectiveness of the 20% sampling plan but not the 40% sampling plan. This is because the 40%/LER sampling plan already acts like 100% and does not benefit from the increased inspection produced by false calls. On the other hand, the 20%/LER sampling plan benefits from the false calls since the initial sample size is not large enough to produce results similar to 100% inspection.

6.0 References

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Appendix A: Results for Tube Maps

Appendix A: Results for Tube Maps

Table A.1. Results for Tube Map 1

POD Curve	Sizing Model	Sample Plan	Tubes Inspected	Ave. Def.	Effectiveness	Efficiency
1	1	S20	722	1.44	0.29	0.37
1	1	S40	1434	3.52	0.70	0.91
1	1	100	3388	3.88	0.78	1.00
2	2	S20	749	2.36	0.47	0.49
2	2	S40	1454	4.68	0.94	0.97
2	2	100	3388	4.84	0.97	1.00
4	1	S20	724	1.40	0.28	0.41
4	1	S40	1436	2.96	0.59	0.87
4	1	100	3388	3.40	0.68	1.00
4	2	S20	731	1.80	0.36	0.40
4	2	S40	1436	4.08	0.82	0.90
4	2	100	3388	4.52	0.90	1.00
5	1	S20	755	1.72	0.34	0.53
5	1	S40	1454	3.08	0.62	0.88
5	1	100	3388	3.24	0.65	1.00
5	2	S20	748	2.32	0.46	0.49
5	2	S40	1455	4.64	0.93	0.98
5	2	100	3388	4.72	0.94	1.00

Table A.2. Results for Tube Map 6

POD Curve	Sizing Model	Sample Plan	Tubes Inspected	Ave. Def.	Effectiveness	Efficiency
1	1	S20	899	3.60	0.36	0.51
1	1	S40	1597	5.96	0.60	0.85
1	1	100	3388	7.00	0.70	1.00
2	2	S20	1026	7.44	0.74	0.75
2	2	S40	1715	9.88	0.99	1.00
2	2	100	3388	9.92	0.99	1.00
4	1	S20	927	4.12	0.41	0.56
4	1	S40	1638	7.04	0.70	0.96
4	1	100	3388	7.36	0.74	1.00
4	2	S20	936	5.64	0.56	0.68
4	2	S40	1633	8.28	0.83	0.95
4	2	100	3388	8.76	0.88	1.00
5	1	S20	1000	5.60	0.56	0.71
5	1	S40	1699	7.84	0.78	1.00
5	1	100	3388	7.84	0.78	1.00
5	2	S20	1034	6.88	0.69	0.75
5	2	S40	1712	9.16	0.92	1.00
5	2	100	3388	9.16	0.92	1.00
6	1	S20	1541	4.76	0.48	0.68
6	1	S40	2336	6.60	0.66	0.94
6	1	100	3388	7.04	0.70	1.00
7	2	S20	1747	7.76	0.78	0.83
7	2	S40	2469	9.32	0.93	1.00
7	2	100	3388	9.32	0.93	1.00

Table A.3. Results for Tube Map 3

POD Curve	Sizing Model	Sample Plan	Tubes Inspected	Ave. Def.	Effectiveness	Efficiency
1	1	S20	747	3.88	0.78	1.00
1	1	S40	1407	3.88	0.78	1.00
1	1	100	3388	3.88	0.78	1.00
2	2	S20	758	4.92	0.98	1.00
2	2	S40	1415	4.92	0.98	1.00
2	2	100	3388	4.92	0.98	1.00

Table A.4. Results for Tube Map 8

POD Curve	Sizing Model	Sample Plan	Tubes Inspected	Ave. Def.	Effectiveness	Efficiency
1	1	S20	900	7.76	0.78	1.00
1	1	S40	1561	7.76	0.78	1.00
1	1	100	3388	7.76	0.78	1.00
2	2	S20	987	9.72	0.97	1.00
2	2	S40	1638	9.72	0.97	1.00
2	2	100	3388	9.72	0.97	1.00

Table A.5. Results for Tube Map 13

POD Curve	Sizing Model	Sample Plan	Tubes Inspected	Ave. Def.	Effectiveness	Efficiency
1	1	S20	1612	85	0.73	0.98
1	1	S40	2073	85	0.73	0.98
1	1	100	3388	87	0.75	1.00
2	2	S20	1734	114	0.98	1.00
2	2	S40	2162	114	0.98	1.00
2	2	100	3388	114	0.98	1.00

Table A.6. Results for Blank Tube Map

Sizing Model	Sample Plan	Tubes Inspected	Tubes Plugged
1	S20	1334	3.9
1	S40	2176	6.6
1	100	3388	9.5
2	S20	1422	0.3
2	S40	2241	0.4
2	100	3388	0.6

Table A.7. Results for Tube Map 1A, POD Curve 4/Sizing Models 1 & 2

POD Curve	Sizing Model	Sample Plan	Tubes Inspected	Ave. Def.	SD	Effectiveness	Efficiency
4	1	STS	495	0.48	1.36	0.10	0.12
4	1	R20	736	1.76	1.13	0.35	0.44
4	1	R22	732	1.72	1.17	0.34	0.43
4	1	R30	1171	1.68	0.69	0.34	0.42
4	1	R32	1166	1.52	0.77	0.30	0.38
4	1	R40	1420	2.64	0.99	0.53	0.65
4	1	R42	1415	2.52	1.00	0.50	0.62
4	1	S20	736	1.76	0.83	0.35	0.44
4	1	S22	731	1.68	0.85	0.34	0.42
4	1	S30	1192	2.40	1.08	0.48	0.59
4	1	S32	1189	2.36	1.04	0.47	0.58
4	1	S40	1420	2.60	1.00	0.52	0.65
4	1	S42	1417	2.56	1.00	0.51	0.64
4	1	100	3388	4.04	0.84	0.81	1.00
4	2	STS	890	1.00	1.85	0.20	0.24
4	2	R20	736	1.88	0.93	0.38	0.43
4	2	R22	733	1.84	0.94	0.37	0.43
4	2	R30	1173	2.24	0.93	0.45	0.52
4	2	R32	1173	2.24	0.93	0.45	0.52
4	2	R40	1418	2.64	1.15	0.53	0.60
4	2	R42	1418	2.64	1.15	0.53	0.60
4	2	S20	738	1.88	0.73	0.38	0.43
4	2	S22	737	1.84	0.69	0.37	0.43
4	2	S30	1189	2.40	1.04	0.48	0.55
4	2	S32	1189	2.40	1.04	0.48	0.55
4	2	S40	1423	2.88	1.20	0.58	0.65
4	2	S42	1422	2.84	1.18	0.57	0.65
4	2	100	3388	4.36	0.70	0.87	1.00

Table A.8. Results for Tube Map 1A, POD Curve 5/Sizing Models 1 & 2

POD Curve	Sizing Model	Sample Plan	Tubes Inspected	Ave. Def.	SD	Effectiveness	Efficiency
5	1	STS	890	1.12	2.05	0.22	0.24
5	1	R20	739	1.68	0.95	0.34	0.39
5	1	R22	734	1.64	0.91	0.33	0.38
5	1	R30	1183	2.20	0.82	0.44	0.56
5	1	R32	1177	2.12	0.88	0.42	0.53
5	1	R40	1428	2.64	1.08	0.53	0.64
5	1	R42	1422	2.60	1.08	0.52	0.63
5	1	S20	745	1.80	0.76	0.36	0.43
5	1	S22	738	1.76	0.83	0.35	0.42
5	1	S30	1201	2.32	0.85	0.46	0.57
5	1	S32	1194	2.20	0.91	0.44	0.54
5	1	S40	1432	2.80	1.04	0.56	0.67
5	1	S42	1426	2.76	1.01	0.55	0.66
5	1	100	3388	4.12	0.83	0.82	1.00
5	2	STS	890	1.16	2.12	0.23	0.24
5	2	R20	736	1.76	1.01	0.35	0.36
5	2	R22	735	1.76	1.01	0.35	0.36
5	2	R30	1197	3.04	1.02	0.61	0.63
5	2	R32	1195	3.00	1.00	0.60	0.63
5	2	R40	1430	2.92	1.15	0.58	0.60
5	2	R42	1429	2.92	1.15	0.58	0.60
5	2	S20	747	2.08	0.64	0.42	0.44
5	2	S22	747	2.08	0.64	0.42	0.44
5	2	S30	1208	2.88	1.05	0.58	0.60
5	2	S32	1205	2.84	1.14	0.57	0.59
5	2	S40	1432	3.08	1.04	0.62	0.64
5	2	S42	1431	3.08	1.04	0.62	0.64
5	2	100	3388	4.80	0.41	0.96	1.00

Table A.9. Results for Tube Map 6A, POD Curve 4/Sizing Models 1 & 2

POD Curve	Sizing Model	Sample Plan	Tubes Inspected	Ave. Def.	SD	Effectiveness	Efficiency
4	1	STS	2205	4.84	3.83	0.48	0.64
4	1	R20	955	5.12	1.76	0.51	0.68
4	1	R22	932	4.68	1.68	0.47	0.62
4	1	R30	1392	6.04	1.40	0.60	0.81
4	1	R32	1370	5.76	1.51	0.58	0.77
4	1	R40	1629	6.64	1.22	0.66	0.90
4	1	R42	1605	6.52	1.19	0.65	0.88
4	1	S20	985	5.76	1.51	0.58	0.77
4	1	S22	951	5.40	1.61	0.54	0.72
4	1	S30	1436	6.48	1.48	0.65	0.87
4	1	S32	1405	6.04	1.57	0.60	0.81
4	1	S40	1637	6.80	1.29	0.68	0.91
4	1	S42	1608	6.40	1.47	0.64	0.85
4	1	100	3388	7.44	1.19	0.74	1.00
4	2	STS	2599	6.96	4.05	0.70	0.76
4	2	R20	935	6.12	1.36	0.61	0.68
4	2	R22	935	6.12	1.36	0.61	0.68
4	2	R30	1382	6.92	1.44	0.69	0.76
4	2	R32	1381	6.92	1.44	0.69	0.76
4	2	R40	1621	8.00	0.82	0.80	0.89
4	2	R42	1621	8.00	0.82	0.80	0.89
4	2	S20	956	6.48	1.00	0.65	0.72
4	2	S22	951	6.44	1.00	0.64	0.72
4	2	S30	1420	7.64	1.22	0.76	0.84
4	2	S32	1419	7.64	1.22	0.76	0.84
4	2	S40	1624	7.96	0.84	0.80	0.89
4	2	S42	1622	7.92	0.86	0.79	0.88
4	2	100	3388	9.04	0.93	0.90	1.00

Table A.10. Results for Tube Map 6A, POD Curve 5/Sizing Models 1 & 2

POD Curve	Sizing Model	Sample Plan	Tubes Inspected	Ave. Def.	SD	Effectiveness	Efficiency
5	1	STS	2205	4.76	3.71	0.48	0.64
5	1	R20	1011	5.64	1.35	0.56	0.76
5	1	R22	964	5.04	1.57	0.50	0.68
5	1	R30	1447	6.52	1.23	0.65	0.88
5	1	R32	1416	6.24	1.33	0.62	0.84
5	1	R40	1667	6.84	1.18	0.68	0.92
5	1	R42	1644	6.68	1.14	0.67	0.90
5	1	S20	1040	6.28	1.17	0.63	0.85
5	1	S22	1000	5.92	1.08	0.59	0.80
5	1	S30	1488	6.80	1.12	0.68	0.91
5	1	S32	1454	6.56	1.19	0.66	0.88
5	1	S40	1685	7.28	1.14	0.73	0.98
5	1	S42	1661	7.16	1.14	0.72	0.96
5	1	100	3388	7.44	1.08	0.74	1.00
5	2	STS	2294	8.36	3.20	0.84	0.88
5	2	R20	989	6.76	1.30	0.68	0.71
5	2	R22	984	6.68	1.28	0.67	0.70
5	2	R30	1450	8.36	1.08	0.84	0.88
5	2	R32	1447	8.32	1.11	0.83	0.87
5	2	R40	1663	8.44	1.04	0.84	0.89
5	2	R42	1661	8.40	1.12	0.84	0.88
5	2	S20	1040	7.72	1.21	0.77	0.81
5	2	S22	1000	7.68	1.22	0.77	0.81
5	2	S30	1488	8.72	0.46	0.87	0.92
5	2	S32	1454	8.68	0.48	0.87	0.91
5	2	S40	1685	9.20	0.71	0.92	0.97
5	2	S42	1661	9.16	0.69	0.92	0.96
5	2	100	3388	9.52	0.59	0.95	1.00

Table A.11. Results for Tube Map 8A, POD Curve 4/Sizing Models 1 & 2

POD Curve	Sizing Model	Sample Plan	Tubes Inspected	Ave. Def	SD	Effectiveness	Efficiency
4	1	STS	2599	5.72	3.41	0.57	0.76
4	1	R20	900	7.48	1.00	0.75	1.00
4	1	R22	884	7.48	1.00	0.75	1.00
4	1	R30	1332	7.48	1.00	0.75	1.00
4	1	R32	1313	7.48	1.00	0.75	1.00
4	1	R40	1556	7.48	1.00	0.75	1.00
4	1	R42	1535	7.44	1.00	0.74	1.00
4	1	S20	908	7.48	1.00	0.75	1.00
4	1	S22	887	7.48	1.00	0.75	1.00
4	1	S30	1341	7.48	1.00	0.75	1.00
4	1	S32	1322	7.48	1.00	0.75	1.00
4	1	S40	1564	7.48	1.00	0.75	1.00
4	1	S42	1545	7.48	1.00	0.75	1.00
4	1	100	3388	7.48	1.00	0.75	1.00
4	2	STS	2336	6.24	4.42	0.62	0.68
4	2	R20	902	9.08	0.81	0.91	1.00
4	2	R22	901	9.08	0.81	0.91	1.00
4	2	R30	1323	9.08	0.81	0.91	1.00
4	2	R32	1323	9.08	0.81	0.91	1.00
4	2	R40	1554	9.08	0.81	0.91	1.00
4	2	R42	1553	9.08	0.81	0.91	1.00
4	2	S20	902	9.08	0.81	0.91	1.00
4	2	S22	900	9.08	0.81	0.91	1.00
4	2	S30	1340	9.08	0.81	0.91	1.00
4	2	S32	1339	9.08	0.81	0.91	1.00
4	2	S40	1560	9.08	0.81	0.91	1.00
4	2	S42	1558	9.08	0.81	0.91	1.00
4	2	100	3388	9.08	0.81	0.91	1.00

Table A.12. Results for Tube Map 8A, POD Curve 5/Sizing Models 1 & 2

POD Curve	Sizing Model	Sample Plan	Tubes Inspected	Ave. Def.	SD	Effectiveness	Efficiency
5	1	STS	2599	6.24	3.71	0.62	0.76
5	1	R20	940	8.28	1.06	0.83	1.00
5	1	R22	916	8.28	1.06	0.83	1.00
5	1	R30	1370	8.28	1.06	0.83	1.00
5	1	R32	1348	8.28	1.06	0.83	1.00
5	1	R40	1584	8.28	1.06	0.83	1.00
5	1	R42	1565	8.28	1.06	0.83	1.00
5	1	S20	948	8.28	1.06	0.83	1.00
5	1	S22	921	8.28	1.06	0.83	1.00
5	1	S30	1377	8.28	1.06	0.83	1.00
5	1	S32	1360	8.28	1.06	0.83	1.00
5	1	S40	1601	8.28	1.06	0.83	1.00
5	1	S42	1577	8.28	1.06	0.83	1.00
5	1	100	3388	8.28	1.06	0.83	1.00
5	2	STS	2468	6.88	4.41	0.69	0.72
5	2	R20	938	9.64	0.57	0.96	1.00
5	2	R22	935	9.64	0.57	0.96	1.00
5	2	R30	1364	9.64	0.57	0.96	1.00
5	2	R32	1363	9.64	0.57	0.96	1.00
5	2	R40	1584	9.64	0.57	0.96	1.00
5	2	R42	1582	9.64	0.57	0.96	1.00
5	2	S20	949	9.64	0.57	0.96	1.00
5	2	S22	945	9.64	0.57	0.96	1.00
5	2	S30	1372	9.64	0.57	0.96	1.00
5	2	S32	1368	9.64	0.57	0.96	1.00
5	2	S40	1606	9.64	0.57	0.96	1.00
5	2	S42	1603	9.64	0.57	0.96	1.00
5	2	100	3388	9.64	0.57	0.96	1.00

Table A.13. Results for Tube Map 13A, POD Curve 4/Sizing Models 1 & 2

POD Curve	Sizing Model	Sample Plan	Tubes Inspected	Ave. Def.	SD	Effectiveness	Efficiency
4	1	STS	3388	87	5.16	0.75	1.00
4	1	R20	1654	85	5.25	0.73	0.98
4	1	R22	1623	84	4.92	0.73	0.98
4	1	R30	1958	85	4.99	0.74	0.99
4	1	R32	1935	85	4.68	0.73	0.98
4	1	R40	2119	85	5.16	0.74	0.99
4	1	R42	2095	85	5.06	0.74	0.99
4	1	S20	1665	85	5.36	0.73	0.98
4	1	S22	1627	84	5.08	0.73	0.97
4	1	S30	1970	86	5.07	0.74	0.99
4	1	S32	1948	85	5.02	0.74	0.99
4	1	S40	2123	86	5.25	0.74	0.99
4	1	S42	2097	85	5.25	0.74	0.99
4	1	100	3388	87	5.16	0.75	1.00
4	2	STS	3388	104	3.15	0.90	1.00
4	2	R20	1655	103	3.37	0.88	0.98
4	2	R22	1648	103	3.38	0.88	0.98
4	2	R30	1949	103	3.09	0.88	0.99
4	2	R32	1945	103	3.09	0.88	0.99
4	2	R40	2115	103	3.37	0.89	0.99
4	2	R42	2110	103	3.37	0.89	0.99
4	2	S20	1664	103	2.87	0.89	0.99
4	2	S22	1659	103	2.87	0.89	0.99
4	2	S30	1968	103	3.11	0.89	0.99
4	2	S32	1961	103	3.14	0.89	0.99
4	2	S40	2114	103	2.83	0.89	0.99
4	2	S42	2109	103	2.83	0.89	0.99
4	2	100	3388	104	3.15	0.90	1.00

Table A.14. Results for Tube Map 13A, POD Curve 5/Sizing Models 1 & 2

POD Curve	Sizing Model	Sample Plan	Tubes Inspected	Ave. Def.	SD	Effectiveness	Efficiency
5	1	STS	3388	92	4.28	0.79	1.00
5	1	R20	1721	91	3.99	0.78	0.99
5	1	R22	1687	91	3.99	0.78	0.99
5	1	R30	2012	91	3.84	0.78	0.99
5	1	R32	1980	91	3.75	0.78	0.99
5	1	R40	2115	92	4.16	0.79	1.00
5	1	R42	2110	92	4.20	0.79	1.00
5	1	S20	1722	91	4.06	0.78	0.99
5	1	S22	1689	91	4.01	0.78	0.99
5	1	S30	2025	92	4.24	0.79	1.00
5	1	S32	1991	91	4.28	0.78	0.99
5	1	S40	2161	92	4.10	0.79	1.00
5	1	S42	2135	91	3.97	0.78	0.99
5	1	100	3388	92	4.28	0.79	1.00
5	2	STS	3388	110	2.03	0.95	1.00
5	2	R20	1721	109	2.14	0.94	0.99
5	2	R22	1713	109	2.10	0.94	0.99
5	2	R30	2000	109	2.11	0.94	0.99
5	2	R32	1995	109	2.11	0.94	0.99
5	2	R40	2162	109	2.07	0.94	0.99
5	2	R42	2157	109	2.07	0.94	0.99
5	2	S20	1717	109	2.02	0.94	0.99
5	2	S22	1711	109	1.96	0.94	0.99
5	2	S30	2023	109	2.12	0.94	0.99
5	2	S32	2015	109	2.08	0.94	0.99
5	2	S40	2162	109	1.93	0.94	0.99
5	2	S42	2156	109	1.90	0.94	0.99
5	2	100	3388	110	2.03	0.95	1.00

Table A.15. Results for Tube Map 20, POD Curve 4/Sizing Models 1 & 2

POD Curve	Sizing Model	Sample Plan	Tubes Inspected	Ave. Def.	SD	Effectiveness	Efficiency
4	1	STS	627	1.44	3.38	0.12	0.16
4	1	R20	719	1.80	1.50	0.15	0.20
4	1	R22	719	1.80	1.50	0.15	0.20
4	1	R30	1181	2.52	1.42	0.21	0.29
4	1	R32	1179	2.52	1.42	0.21	0.29
4	1	R40	1430	3.24	1.39	0.27	0.38
4	1	R42	1428	3.24	1.39	0.27	0.38
4	1	S20	734	1.92	1.80	0.16	0.22
4	1	S22	734	1.92	1.80	0.16	0.22
4	1	S30	1202	2.92	0.95	0.24	0.34
4	1	S32	1201	2.92	0.95	0.24	0.34
4	1	S40	1438	3.76	1.96	0.31	0.43
4	1	S42	1436	3.76	1.96	0.31	0.43
4	1	100	3388	8.56	1.61	0.71	1.00
4	2	STS	1153	3.52	5.25	0.29	0.32
4	2	R20	742	2.72	1.10	0.23	0.25
4	2	R22	742	2.72	1.10	0.23	0.25
4	2	R30	1198	4.24	1.27	0.35	0.39
4	2	R32	1198	4.24	1.27	0.35	0.39
4	2	R40	1438	4.80	1.53	0.40	0.44
4	2	R42	1438	4.80	1.53	0.40	0.44
4	2	S20	732	2.24	1.96	0.19	0.20
4	2	S22	732	2.24	1.96	0.19	0.20
4	2	S30	1201	3.56	0.82	0.30	0.33
4	2	S32	1201	3.56	0.82	0.30	0.33
4	2	S40	1438	4.44	1.89	0.37	0.41
4	2	S42	1438	4.44	1.89	0.37	0.41
4	2	100	3388	10.80	1.04	0.90	1.00

Table A.16. Results for Tube Map 20, POD Curve 5/Sizing Models 1 & 2

POD Curve	Sizing Model	Sample Plan	Tubes Inspected	Ave. Def.	SD	Effectiveness	Efficiency
5	1	STS	1153	2.92	4.41	0.24	0.32
5	1	R20	733	2.04	1.02	0.17	0.23
5	1	R22	732	2.04	1.02	0.17	0.23
5	1	R30	1197	3.12	1.69	0.26	0.34
5	1	R32	1193	3.12	1.69	0.26	0.34
5	1	R40	1443	3.88	1.45	0.32	0.43
5	1	R42	1438	3.88	1.45	0.32	0.43
5	1	S20	736	1.96	1.65	0.16	0.22
5	1	S22	736	1.96	1.65	0.16	0.22
5	1	S30	1209	2.96	0.98	0.25	0.33
5	1	S32	1204	2.96	0.98	0.25	0.33
5	1	S40	1442	3.52	1.94	0.29	0.39
5	1	S42	1438	3.52	1.94	0.29	0.39
5	1	100	3388	9.00	1.19	0.75	1.00
5	2	STS	1284	3.96	5.42	0.33	0.36
5	2	R20	735	2.32	1.44	0.19	0.21
5	2	R22	735	2.32	1.44	0.19	0.21
5	2	R30	1188	3.44	1.53	0.29	0.30
5	2	R32	1188	3.44	1.53	0.29	0.30
5	2	R40	1434	4.36	1.93	0.36	0.39
5	2	R42	1434	4.36	1.93	0.36	0.39
5	2	S20	736	2.28	1.97	0.19	0.20
5	2	S22	736	2.28	1.97	0.19	0.20
5	2	S30	1207	3.76	1.01	0.31	0.33
5	2	S32	1207	3.76	1.01	0.31	0.33
5	2	S40	1441	4.60	1.98	0.38	0.40
5	2	S42	1441	4.60	1.98	0.38	0.40
5	2	100	3388	11.36	0.81	0.95	1.00

Table A.17. Results for Tube Map 21, POD Curve 4/Sizing Models 1 & 2

POD Curve	Sizing Model	Sample Plan	Tubes Inspected	Ave. Def.	SD	Effectiveness	Efficiency
4	1	STS	364	0.20	0.71	0.07	0.08
4	1	R20	688	0.44	0.58	0.15	0.17
4	1	R22	688	0.44	0.58	0.15	0.17
4	1	R30	1136	0.84	0.62	0.28	0.34
4	1	R32	1136	0.84	0.62	0.28	0.34
4	1	R40	1375	0.92	0.81	0.31	0.35
4	1	R42	1375	0.92	0.81	0.31	0.35
4	1	S20	692	0.48	0.51	0.16	0.21
4	1	S22	692	0.48	0.51	0.16	0.21
4	1	S30	1149	0.84	0.80	0.28	0.30
4	1	S32	1149	0.84	0.89	0.28	0.30
4	1	S40	1377	1.04	0.54	0.35	0.42
4	1	S42	1377	1.04	0.54	0.35	0.42
4	1	100	3388	2.56	0.58	0.85	1.00
4	2	STS	364	0.24	0.83	0.08	0.08
4	2	R20	688	0.52	0.71	0.17	0.18
4	2	R22	688	0.52	0.71	0.17	0.18
4	2	R30	1139	0.96	0.68	0.32	0.33
4	2	R32	1139	0.96	0.68	0.32	0.33
4	2	R40	1376	1.16	0.80	0.39	0.40
4	2	R42	1376	1.16	0.80	0.39	0.40
4	2	S20	693	0.56	0.51	0.19	0.19
4	2	S22	693	0.56	0.51	0.19	0.19
4	2	S30	1149	0.96	0.79	0.32	0.33
4	2	S32	1149	0.96	0.79	0.32	0.33
4	2	S40	1377	1.12	0.44	0.37	0.38
4	2	S42	1377	1.12	0.44	0.37	0.38
4	2	100	3388	2.92	0.40	0.97	1.00

Table A.18. Results for Tube Map 21, POD Curve 5/Sizing Models 1 & 2

POD Curve	Sizing Model	Sample Plan	Tubes Inspected	Ave. Def.	SD	Effectiveness	Efficiency
5	1	STS	101	0	0	0	0
5	1	R20	692	0.52	0.87	0.17	0.20
5	1	R22	692	0.52	0.87	0.17	0.20
5	1	R30	1137	0.80	0.76	0.27	0.32
5	1	R32	1137	0.80	0.76	0.27	0.32
5	1	R40	1373	0.88	0.83	0.29	0.32
5	1	R42	1373	0.88	0.83	0.29	0.32
5	1	S20	694	0.52	0.51	0.17	0.21
5	1	S22	694	0.52	0.51	0.17	0.21
5	1	S30	1149	0.88	0.73	0.29	0.37
5	1	S32	1149	0.88	0.73	0.29	0.37
5	1	S40	1378	1.00	0.58	0.33	0.39
5	1	S42	1378	1.00	0.58	0.33	0.39
5	1	100	3388	2.60	0.65	0.87	1.00
5	2	STS	101	0.00	0.00	0.00	0.00
5	2	R20	695	0.68	0.69	0.23	0.23
5	2	R22	695	0.68	0.69	0.23	0.23
5	2	R30	1136	0.80	0.71	0.27	0.28
5	2	R32	1136	0.80	0.71	0.27	0.28
5	2	R40	1382	1.68	0.90	0.56	0.57
5	2	R42	1382	1.68	0.90	0.56	0.57
5	2	S20	693	0.56	0.51	0.19	0.19
5	2	S22	693	0.56	0.51	0.19	0.19
5	2	S30	1149	0.92	0.81	0.31	0.31
5	2	S32	1149	0.92	0.81	0.31	0.31
5	2	S40	1378	1.16	0.47	0.39	0.40
5	2	S42	1378	1.16	0.47	0.39	0.40
5	2	100	3388	2.88	0.33	0.96	1.00

Table A.19. Results for GER Expansion Rule, POD Curve 4/Sizing Model 1

POD Curve	Sizing Model	Sample Plan	Tubes Inspected	Ave. Def.	SD	Effectiveness	Efficiency
Map 1							
4	1	S22	2954	3.60	1.70	0.72	0.84
4	1	S32	3207	3.88	1.33	0.77	0.91
4	1	S42	3388	4.24	0.66	0.84	1.00
4	1	100	3388	4.24	0.66	0.84	1.00
Map 6							
4	1	S22	3388	7.68	1.37	0.76	1.00
4	1	S32	3388	7.68	1.37	0.76	1.00
4	1	S42	3388	7.68	1.37	0.76	1.00
4	1	100	3388	7.68	1.37	0.76	1.00
Map 20							
4	1	S22	3171	8.20	2.88	0.68	0.92
4	1	S32	3388	8.84	1.51	0.73	1.00
4	1	S42	3388	8.84	1.51	0.73	1.00
4	1	100	3388	8.84	1.51	0.73	1.00
Map 21							
4	1	S22	1436	0.89	1.32	0.26	0.37
4	1	S32	2304	1.12	1.23	0.37	0.51
4	1	S42	2900	1.88	1.16	0.62	0.87
4	1	100	3388	2.16	0.80	0.72	1.00

Table A.20. Results for GER Expansion Rule, POD Curve 5/Sizing Model 2

POD Curve	Sizing Model	Sample Plan	Tubes Inspected	Ave. Def.	SD	Effectiveness	Efficiency
Map 1							
5	2	S22	3388	4.80	0.40	0.96	1.00
5	2	S32	3388	4.80	0.40	0.96	1.00
5	2	S42	3388	4.80	0.40	0.96	1.00
5	2	100	3388	4.80	0.40	0.96	1.00
Map 6							
5	2	S22	3388	9.36	0.70	0.93	1.00
5	2	S32	3388	9.36	0.70	0.93	1.00
5	2	S42	3388	9.36	0.70	0.93	1.00
5	2	100	3388	9.36	0.70	0.93	1.00
Map 20							
5	2	S22	3388	11.48	0.71	0.95	1.00
5	2	S32	3388	11.48	0.71	0.95	1.00
5	2	S42	3388	11.48	0.71	0.95	1.00
5	2	100	3388	11.48	0.71	0.95	1.00
Map 21							
5	2	S22	2412	1.80	1.41	0.60	0.63
5	2	S32	3207	2.60	0.86	0.86	0.91
5	2	S42	3306	2.76	0.66	0.92	0.97
5	2	100	3388	2.84	0.37	0.94	1.00

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11. ABSTRACT (200 words or less)

This report summarizes the results of three previous studies to evaluate and compare the effectiveness of sampling plans for steam generator tube inspections. An analytical evaluation and Monte Carlo simulation techniques were the methods used to evaluate sampling plan performance. To test the performance of candidate sampling plans under a variety of conditions, ranges of inspection system reliability were considered along with different distributions of tube degradation. Results from the eddy current reliability studies performed with the retired-from-service Surry 2A steam generator were utilized to guide the selection of appropriate probability of detection and flaw sizing models for use in the analysis. Different distributions of tube degradation were selected to span the range of conditions that might exist in operating steam generators. The principal means of evaluating sampling performance was to determine the effectiveness of the sampling plan for detecting and plugging defective tubes. A summary of key results from the eddy current reliability studies is presented. The analytical and Monte Carlo simulation analyses are discussed along with a synopsis of key results and conclusions.

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