EVALUATING POD/CL CHARACTERIZATIONS OF NDE RELIABILITY

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INTRODUCTION

The damage tolerance approach to structural safety is based on the predicted growth of the "largest" crack that could be present in a structure at the start of a usage period\(^1-4\). The length, \(a_{\text{NDE}}\), of this potential crack has generally been determined by correlating crack size with the reliability of the non-destructive evaluation (NDE) system employed during structural inspections. Since many factors other than crack length influence detectability, NDE reliability as a function of crack length must be expressed as a probability of detection (POD) and must be estimated from a demonstration experiment whose results are non-deterministic.

To reflect the statistical nature of NDE reliability, \(a_{\text{NDE}}\) values have generally been specified in terms of a high confidence (CL) that a high percentage (POD) of all cracks greater than \(a_{\text{NDE}}\) (the POD/CL limit) will be detected. For example, Wood and Engle\(^5\) state that the MIL-A-83444 values of \(a_{\text{NDE}}\) for slow crack growth structure were selected as the 90/95 crack lengths, i.e., there is 95 percent confidence that at least 90 percent of all cracks of length \(a_{\text{NDE}}\) would be detected. While the 90/95 limit has been used to define \(a_{\text{NDE}}\) values in Air Force applications, its justification has been based primarily on engineering judgement that the resulting initial crack size assumptions were sufficiently conservative.

This paper presents the results of a study whose objectives were to compare alternative methods of calculating POD/CL limits and to evaluate the POD/CL characterizations of NDE reliability. The results are based on a Monte Carlo type simulation of NDE evaluation.
demonstration experiments. The simulation process permitted repeating "experiments" under fixed and known conditions. The resulting data were analyzed using binomial and regression analysis methods. For each simulated experiment, the crack lengths corresponding to POD values of 0.5, 0.75, 0.9, 0.95, and 0.99 were estimated and confidence limits were placed on each estimate. The results demonstrate the large degree of scatter that may be present in these one-number characterizations of NDE capability and also show that the amount of scatter depends on the POD function, analysis method, POD value, degree of confidence, and number and size of cracks in the demonstration program.

BACKGROUND

The results from an NDE reliability demonstration program comprise ordered pairs (a_i, Z_i) where a_i is the crack size of the i-th sample specimen and Z_i=1 if the i-th crack was detected by the NDE system and Z_i=0 if the i-th crack was not detected. Such data have traditionally been analyzed using binomial distribution methods. More recently, analysis methods have been devised which are based on assuming a model for the probability of detection as a function of crack length, the POD(a) function.

In the binomial analysis approach, the results are grouped into intervals of crack length. It is assumed that all cracks within a specified interval have approximately the same POD. The number of detections for each group is modeled by the binomial distribution and lower confidence bounds are calculated for the true but unknown value of POD using standard statistical methods. The POD/CL limit is usually taken to be the lowest crack length (if any) at which the lower CL confidence limit reaches the POD value. Different POD/CL limits can be obtained from a single set of data depending on the assignment of cracks to groups. In an extensive study of data sets and binomial analysis methods, Yee, et al., recommended the use of a grouping algorithm identified as the optimized probability method (OPM). This algorithm groups the experimental results so as to achieve the highest possible lower confidence bound on the POD estimates. The OPM was selected in this current study to represent the results of the binomial analysis method.

The analysis approach based on the assumption of a specific equation for POD(a) is called the regression approach in this paper. The rationale for this name is as follows. Since many attributes other than length influence the chances of detecting a crack, different cracks of the same length have different detection probabilities. If a distribution of detection probabilities is postulated for all cracks of length "a" in the population of interest, then the POD(a) is the mean of this distribution.
Calculation is illustrated in Figure 1. In this framework, the POD(a) function is the curve through the means of the crack detection probabilities, i.e., a regression function. Given a specific functional form for POD(a), standard regression techniques can be used to estimate the parameters of the function and to place a lower confidence bound on the function. POD/CL limits can then be calculated from the lower bound function.

For the data in Lewis, et al., 8 (the so-called "Have Cracks-Will Travel" data) the log-linear logistics or log-odds model was determined to provide an acceptable fit. 9 The functional form of this model is given by

\[
POD(a) = \frac{\exp(\alpha + \beta \ln a)}{1 + \exp(\alpha + \beta \ln a)}
\]

(1)

or

\[
\ln \left( \frac{POD(a)}{1-POD(a)} \right) = \alpha + \beta \ln a
\]

(2)

For this reason, the log-odds model was chosen for simulating the NDE reliability experiments of this study. The scatter of the individual crack detection probabilities about the POD(a) function was selected to reflect the scatter exhibited in the "Have Cracks"

Figure 1. Schematic Representation of Distribution of Detection Probabilities for Cracks of Fixed Length.
data. It is recognized that different models may be more appropriate for different data sets. However, the major conclusions of this study were judged to be insensitive to the specific choice of any model which is representative of real NDE reliability demonstration programs.

EVALUATION OF NDE ANALYSIS METHODS

To evaluate and compare the various methods for analyzing data from NDE capability demonstration programs, results from a large number of experiments under known conditions are necessary. Since such tests are expensive and the experimental conditions are difficult to hold fixed over the long intervals necessary to repeat experiments, "experimental" NDE data were generated in a computer simulation of inspections. The simulation process enabled the generation of a large number of NDE experiments under a "known capability" and under selected changes in experimental conditions.

Simulation Procedure

Figure 2 presents a schematic diagram for the process of simulating NDE experiments. The process simulates one NDE experiment by simulating the results of one inspection of each of 400 details with cracks of different lengths. The simulation of the

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Figure 2. Schematic of Procedure for Simulating NDE Experiments.
inspection of each detail requires three steps:

(1) To reflect the random nature of the crack sizes that may be present in the details to be inspected, a distribution of crack sizes is assumed. A simulated inspection is initiated by selecting a crack size at random, \( a_i \), from this distribution to represent the length of the \( i \)th crack. The assumed crack size distribution was considered to be an experimental condition.

(2) A detection probability, \( p_i \), is determined for this \( i \)th crack using the model

\[
Y_i = \alpha + \beta \ln a_i + \epsilon_i, \quad (3)
\]

where

\[
Y_i = \ln \left( \frac{p_i}{1 - p_i} \right);
\]

\( \alpha \) and \( \beta \) are constants which define the POD capability of the NDE system; and

\( \epsilon_i \) is randomly selected from a normal distribution with zero mean and standard deviation, \( S(e) \), chosen to reflect the variability of the detection probabilities about the POD curve.

To simulate the "Hard Cracks" data, \( S(e) \) was set equal to the standard error as determined during the regression of analysis which was performed to obtain representative values of \( \alpha \) and \( \beta \). Solving equation (3) for \( p_i \) yields the randomly determined detection probability for the \( i \)th crack was given by

\[
p_i = \frac{\exp (\alpha + \beta \ln a_i + \epsilon_i)}{1 + \exp (\alpha + \beta \ln a_i + \epsilon_i)}, \quad (4)
\]

(3) Given the detection probability, \( p_i \), for the crack, a simple Bernoulli trial is simulated with probability \( p_i \) of successfully detecting the crack and \( (1-p_i) \) of failing to detect it. The result of the "inspection" is recorded either as \( (a_i, 1) \) if the "crack" was "detected" or \( (a_i, 0) \) if the "crack" was not "detected."

After the above steps are repeated 400 times to complete an entire experiment, the data were analyzed by the different analysis methods. These included the methods based on the binomial distribution and the regression analysis using the log odds model. Upper confidence limits on crack sizes (POD/CL limits) were calculated using all combinations of POD equal to 0.5, 0.75, 0.9, 0.95 and 0.99 and confidence limits for 90, 95 and 99 percent.

The above procedure was repeated to generate 100 repetitions of the basic NDE reliability experiment and the associated estimates
of the POD(a) function and the POD/CL values. These data formed
the basis for the comparison and evaluation of the various methods
for estimating the capability of an NDE system.

While all of the large data sets of the "Have Cracks" data
have been simulated, this paper focuses only on the simulation
of the eddy current surface scans around countersunk fasteners
in a skin and stringer wing assembly. This data set is typical of
the "Have Cracks" data. The original data points are shown in
Figure 3 in which each data point represents the percent of
detections of a particular crack in 60 inspections. The mean
(solid) line of Figure 3 was taken as the true POD(a) and for
this curve \( \alpha = -2.9 \) and \( \beta = 1.7 \). For this NDE capability, 90
percent of 20.1mm cracks and 95 percent of 31.1mm cracks will be
detected.

Two crack-size distributions were used in the simulated
experiments. First, the distribution of the reported crack sizes

![Figure 3](image-url)
of the original data set was employed but these crack sizes were too short for use in the binomial analysis method for the NDE capability assumed. These cracks had a median of 5.8mm and a 90th percentile of 12.7mm. To effect a comparison between the binomial and regression analysis methods, a distribution of longer cracks was introduced. This distribution was arbitrarily assumed to be lognormal with a median crack length of 12.7mm and 90th percentile of 76.2mm.

Most of the simulations were performed using the scatter in detection probabilities about the POD(a) as displayed in Figure 3. However, to evaluate the effect of this scatter on the POD/CL estimates, one set of experiments was simulated in which it was assumed that there was no scatter in individual crack detection probabilities about the POD(a) function (i.e., $S(r)=0$).

Comparison of Binomial and Regression Analysis Methods

In the initial attempt to compare the binomial and regression analysis methods, the crack-size distribution reported for the "Have Cracks" data were used in the simulation. For this crack-length distribution, the binomial methods always failed to yield estimates for the 90/95 and 95/90 crack length values. For this range of crack lengths in the experiment and for the NDE capability implicitly assumed by the POD(a) function, it was extremely unlikely to obtain any crack length interval which would yield sufficient detections to have 95 percent confidence that 90 percent of all cracks of that length would be found. The regression method, however, always produces a POD/CL value, albeit extremely large in some cases.

When the larger cracks were used in the NDE simulation experiments, the OPM yielded 90/95 limits in 87 percent of the trials and 95/90 limits in 17 percent of the trials. A more detailed method for comparing the POD/CL estimates from the two analysis methods is to compare the observed distributions of the estimates that were obtained during the 100 simulated experiments. Figure 4 shows the observed distributions of the 90/95 estimates for the regression and OPM analysis methods. In the figure, the vertical scale gives the percentage of the 90/95 estimates which are less than the indicated crack length. For example, using the regression analysis, 50 percent of the 90/95 estimates were less than 40mm while using the OPM analysis, 50 percent of the 90/95 estimates were less than 65mm.

The distributions of Figure 4 indicate that the regression estimates are more precise in that they have far less variability and that they are generally closer to the "true" 90th percentile crack length of 20.1mm. Both analysis methods produced estimates which were always above the "true" value but the lack of
reproducibility in either of the estimates casts doubts on their usefulness. For example, assume the distributions are representative of the scatter in the estimates from a fixed but unknown set of conditions. If a single NDE experiment of 400 inspections is to be performed and the data analyzed using the regression approach, there would be a 20 percent chance that the 90/95 estimate would be less than 35mm but also a 20 percent chance that the 90/95 estimate would be greater than 50mm. This much potential scatter could greatly influence inspection schedules or risk analysis if the 90/95 value were to be used as a NDE.

Comparison of POD/CL Limits

The choice of the POD/CL combination to be used in defining the capability of an NDE system has been rather arbitrarily defined as 90/95. To evaluate various choices from the viewpoint of their estimates in an NDE evaluation experiment, the crack lengths corresponding to several combinations of POD and confidence level were calculated for each simulated experiment. The statistical properties of these POD/CL limits under fixed conditions provided considerable insight into the practical usefulness of various combinations.
Table 1 presents the mean ($\bar{X}$), standard deviation ($S$), and coefficient of variation ($CV = 100 \frac{S}{\bar{X}}$) of the estimates of POD/CL limits obtained from the regression analysis. The statistics are based on one sample of 100 simulated experiments. The observed percentage of POD/CL values greater than the true POD crack length, $a_p$, was always greater than or equal to the theoretical CL value. Thus, the calculated POD/CL values were conservative.

The coefficient of variation columns of the tables display that estimation precision decreases rapidly with increasing POD and with increasing level of confidence. Further, the average of the calculated POD/CL limits increases as the degree of confidence increases as would be expected. The combination of these facts indicates that considerable real scatter is present in the estimate of NDE capability at high values of POD and confidence.

Table 1. Means, Standard Deviations, and Coefficients of Variation for Combinations of POD/CL

<table>
<thead>
<tr>
<th>POD</th>
<th>CL</th>
<th>$a_p$ (mm)*</th>
<th>LOG ODDS–REG.</th>
<th></th>
<th></th>
<th></th>
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<tr>
<td></td>
<td></td>
<td></td>
<td>$\bar{X}$ (mm)</td>
<td>$S$ (mm)</td>
<td>CV (%)</td>
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<tr>
<td>0.5</td>
<td>0.5</td>
<td>5.5</td>
<td>5.6</td>
<td>0.4</td>
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<td>0.9</td>
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<td></td>
<td>6.1</td>
<td>0.5</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>0.95</td>
<td></td>
<td></td>
<td>6.4</td>
<td>0.5</td>
<td>8</td>
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<tr>
<td>0.99</td>
<td></td>
<td></td>
<td>6.9</td>
<td>0.7</td>
<td>10</td>
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<tr>
<td>0.75</td>
<td>0.5</td>
<td>10.5</td>
<td>11.4</td>
<td>1.6</td>
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<td>3.0</td>
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<tr>
<td>0.95</td>
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<td></td>
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<tr>
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<td></td>
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<td>45.0</td>
<td>31.8</td>
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<tr>
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<td></td>
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<td>433.8</td>
<td>354</td>
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<tr>
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<td>31.1</td>
<td>40.4</td>
<td>15.5</td>
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<tr>
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<tr>
<td>0.99</td>
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<td></td>
<td>747.3</td>
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<tr>
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<td>838.8</td>
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<td></td>
<td></td>
<td>802.9</td>
<td>**</td>
<td>409</td>
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<tr>
<td>0.99</td>
<td></td>
<td></td>
<td>**</td>
<td>**</td>
<td>969</td>
<td></td>
</tr>
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</table>

** indicates value was larger than 1,000.

* $a_p$ indicates crack length for which 100 POD percent of cracks would be detected.
As another example of the effect of scatter in the estimates, assume an $a_{NDE}$ value is to be determined and the data will be analyzed using the regression approach. Figure 5 displays the distribution of potential estimates of $a_{NDE}$ if $a_{NDE}$ is defined as either the 90/95 or 95/90 limit. The result of the future experiment is equivalent to drawing a number at random from either of these cumulative distribution functions. For this NDE capability, the "true" 90th percentile of POD is 20.1mm but there is a 50 percent chance that the 90/95 estimate will exceed 40mm, a 25 percent chance that the estimate will exceed 48mm, and a 10 percent chance that the estimate will exceed 55mm. These values can be read from the 90/95 curve of Figure 5. Similarly, the "true" 95th percentile is 31.1mm while there is a 50 percent chance that the 95/90 estimate will exceed 75mm and a 22 percent chance the estimate will exceed 100mm.

In general, for this NDE capability the scatter in the estimates is sufficiently large as to cast considerable doubt on the validity of any single POD/CL limit if the POD is 0.9 or greater and the level of confidence is 0.9 or greater. It should be noted that the scatter in the limits gives rise to excessively large estimates of $a_{NDE}$ and the estimates are conservative. However, the degree of conservativeness would be unknown in a particular application.

![Figure 5. Observed Distributions of 90/95 and 95/90 Estimates from Regression Analysis Method.](image-url)
Influence of Crack Sizes in NDE Experiments

To compare the binomial and regression model methods of analysis, it was necessary to introduce a distribution of long cracks for the representative "specimens" of the simulation. When the resulting POD/CL estimates from the long cracks simulation were compared to those of the short cracks (i.e. the crack sizes of the "Have Cracks" data) simulations, it was observed that significantly different distributions resulted, Figure 6. In all cases considered, the long-crack experiments had less scatter in the POD/CL estimates than did the experiments with short cracks.

While the effect of specimen crack-size distribution has not been sufficiently determined, these comparisons definitely indicate that the sizes of the cracks in a NDE capability demonstration program are an important experimental factor.

Influence of Scatter in Detection Probabilities at a Crack Length

In an effort to isolate the causes of the large degree of scatter in the estimates of the POD/CL limits, it was postulated that this scatter could be caused by the relatively poor correlation of crack detection with crack length that was present in the "Have Cracks" data. To test this hypothesis, NDE simulations were performed with standard error of deviations about the POD function.

Figure 6. Observed Distributions of 90/95 Estimates from Regression Analysis of Long and Short Crack Experiments.
reduced to zero. That is, it was assumed that all cracks of a given length had exactly the crack-detection probability as given by the POD(a) function. The relative degrees of scatter and the resulting distributions of 90/95 limits are shown in Figure 7. In Figure 7a, the outside bands are 95 percent confidence limits on the detection probabilities as derived from the "Have Cracks" data; i.e., these are 95 percent confidence bounds for the individual data points of Figure 3. The center curve is the assumed POD(a) function. Figure 7b presents the cumulative distributions of 90/95 estimates from the normal scatter and no scatter simulated experiments. Reducing the scatter about the POD(a) function to zero, reduced the variability of the POD/CL estimates but not by a practically significant amount.

DISCUSSION

Analysis of the results of the simulated NDE experiments lead to three major conclusions:

1) The large degree of variability in the POD/CL crack length estimates for POD values of 0.9 and greater indicates that such estimates are not reproducible if an NDE capability experiment of the sample size simulated herein would be repeated.

Figure 7. Evaluation of Scatter in Detection Probability.
2) Both the magnitude and scatter in the POD/CL estimates are significantly influenced by the crack sizes in the experiment.

3) The variability of the POD/CL estimates is not primarily due to the lack of a strong correlation of detection probabilities of individual cracks with crack length.

These conclusions imply that the scatter in the POD/CL estimates is inherent to the analysis procedure and the sample size, but only indirectly to the NDE capability. The simulated experiments of this study were based on inspections of 400 cracks. These would be considered as large experiments due to the difficulty of obtaining representative, cracked structural specimens. Thus, while increasing the sample size would increase the precision of the POD/CL estimates, the very large sample sizes required for a significant decrease in scatter would not be practical.

To further explore the instability of crack length estimates corresponding to high POD values, consider the shape of the model for the POD(a) function. Available data from NDE reliability experiments indicate that at least some of the longer length cracks fail to be detected on occasion. Realistic POD models will account for these misses by asymptotically approaching one. Simple geometric considerations lead to the conclusion that estimates of crack lengths corresponding to POD values in the flat portion of the curve are very sensitive to sampling errors in the estimated POD values (Figure 3). Since the POD value is being estimated statistically, very large sample sizes would be required to reduce the sampling error in the POD estimate to yield a precise corresponding crack length.

It is theoretically possible to have an NDE system for which the slope of the POD curve is sufficiently steep that reasonably precise estimates of the crack length corresponding to a POD of 0.90 or 0.95 can be obtained. Such POD curves have not yet been shown to occur in field applications, since human factors as well as inspection hardware influence the capability of the system. Even if such a system were available, however, attempts to characterize it in terms of higher POD levels (say 0.99 or 0.999) would lead to the same lack of precision in the POD/CL estimates.

For the damage tolerance analyses, other types of characterization of NDE capability may be required. For example, the quantity of real interest is the probability that cracks longer than \( a_{NDE} \) will pass undetected. This probability depends on both the POD(a) function and the sizes of the cracks that are being inspected. In particular, let \( H(a) \) represent the probability of having a crack greater than or equal to "a" in the structure and failing to detect it during an inspection. Then

\[
H(a) = \int_a^\infty [1 - POD(x)] f(x) \, dx ,
\]

(5)
where \( f(x) \) is the probability density function of the crack sizes in the structure. Conversely, if an acceptable risk, \( q \), of missing a crack can be specified, a meaningful single-number characterization of the inspection reliability can be calculated as

\[
a_{\text{NDE}}^{*} = H^{-1}(q) \quad (6)
\]

Thus, there is a probability of \( q \) that a crack larger than \( a_{\text{NDE}}^{*} \) will be in the structure and not detected. Since the damage tolerance analyses are designed to insure that a crack of length \( a_{\text{NDE}} \) will not grow to failure during the next usage period, \( q \) is an upper bound on the probability of structural failure during the period. This approach to characterizing NDE reliability is currently under study.

CONCLUSIONS

1) Given an acceptable model for the regression function, the regression estimates of NDE capability expressed in terms of a confidence limit on a high probability of detection value (i.e., a POD/CL value) are superior to those derived using binomial distribution theory. The regression estimates are closer to the true POD, exhibit less scatter in the distribution of the estimates, and, contrary to binomial methods, always provide an estimate of the desired limit.

2) For the NDE experiments simulated, the magnitude and scatter of the POD/CL values are significantly influenced by the crack sizes employed in the NDE capability experiment.

3) For the NDE experiments simulated, the degree of scatter of the detection probabilities of individual cracks about the POD function has only a secondary effect on the scatter in the POD/CL estimates.

4) For the NDE experiments simulated, single-number characterizations of NDE capability expressed in terms of a probability of detection and a confidence level (POD/CL) display a degree of scatter (i.e., non-reproducibility) that make these characterizations of limited practical use in the evaluation of NDE systems.

ACKNOWLEDGEMENT

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REFERENCES


DISCUSSION

S. Bush (Battelle, Pacific Northwest Laboratory): I noticed you used the Lockheed data. The result of using these data and the plate inspection steering committee data (which was the European program), and the pressure vessel research (which was on different material but the same philosophy), is that what you really have on your POD's are two totally different statistical populations as far as the operators are concerned. In other words, the operator variables are extremely important. Once you will find that part of it is 90-95 and the great mass of them will be, perhaps, 50-95 for the same population of cracks. This means you now have two probability density functions that are really not additive, and you have to handle them separately. What do you do with them? You can do sensitivity analysis. In fact, your last points with regard to the structural significance obviously are very important. Have you considered
this one, this business of handling two populations that are sen-
sitive to one major parameter, such as the operator?

A. P. Berens (University of Dayton): I think the results are some-
what insensitive to the fact that I did use the Lockheed data. The 
main thrust of your question really addressed the super-
importance of safety in the right population, of making sure that 
the inspectors you are using are those that you will have in the 
field, and if you have a mix of those kinds of inspectors, that 
is what you need in the characterization of POD capability. So 
until you can prove that you have only one or the other in the 
field, I think you have to keep them both. They are the statis-
tics.

S. Bush: I agree with you completely. In fact, I have seen the case 
where they take the two populations and mix them and what comes 
out of that is an indication that no one does very well which, of 
course, is totally wrong.