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ANALYSIS OF PVRC 251J SECTIONING DATA (1984) AND ROUND ROBIN ULTRASONIC TEST DATA (1968) FOR ESTIMATING RELIABILITY OF FLAW FABRICATION AND NDE PROCEDURE

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# Analysis of PVRC 251J Sectioning Data (1984) and Round Robin Ultrasonic Test Data (1968) for Estimating Reliability of Flaw Fabrication and NDE Procedure

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Abstract:

Based on the 1984 sectioning data of an 11-inch thick plate weld specimen containing 15 implanted flaws, and the round robin ultrasonic testing data of that specimen for flaw detection by 5 teams using a 1968 ultrasonic testing procedure (UT-1968), the reliability of flaw fabrication in a test specimen for dimensional stability and that of a flaw detection procedure, UT-1968, are assessed.

The analysis uses an expert-system approach where mainframe and personal computer (PC) software for database, graphics, and analysis are integrated with decision-support criteria for a problem-specific automated data analysis methodology.

The main results of the reliability study are:

(a) The flaw fabrication procedure is dimensionally unsatisfactory for cross cracks and longitudinal cracks, but is "reliable" for slag inclusions if a size amplification factor of 2 is acceptable.

(b) The detection threshold for zero false call probability is 2.0 inches for teams A, B, and C using the UT-1968 procedure.

(c) The ultrasonic detection procedure, UT-1968, is less than 90% reliable if the prescribed threshold for a true flaw to be in the neighborhood of an indication is 2.0 inches (center-to-center).

Significance of these results and the analysis methodology in assessing and improving weld flaw detection procedures is discussed.

Keywords: Analysis of variance; confidence level; data analysis; database management; flaw fabrication reliability; NDE reliability; reliability modeling; round robin test; statistical analysis; tolerance factors; ultrasonic testing; weld flaw detection.

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The names of computer systems or software products mentioned in this report imply neither approval nor endorsement by the author or the organizations that support this work.

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* Name of an individual who has since left NBS.

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Analysis of PVRC 251J Sectioning Data (1984) and Round Robin Ultrasonic Test Data (1968) for Estimating Reliability of Flaw Fabrication and NDE Procedure

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## 1. Introduction

Since the early 1960's, the reliability of the nondestructive evaluation (NDE) of critical structures for flaw detection, location, and sizing, has been of considerable interest to the engineering community and the public at large.

Two events were generally credited by engineers for motivating them to accelerate the development of the art and technology of NDE into a discipline where generic questions on NDE capabilities could be carefully examined and answered.

The first came from a demand for better NDE in the space and nuclear industries where safety considerations were given a higher priority. The second was due to the significant advances in fracture mechanics where "under-sized" flaws in non-critical regions of components or structures were shown to be acceptable during service, and the burden of implementing this theory fell on the NDE engineers for improving the reliability of not only detecting flaws but also locating and sizing them through new techniques and procedures.

As part of the industry's response to this need, the Pressure Vessel Research Committee (PVRC) of the Welding Research Council initiated in 1965 a long-term research program where 12 plate-weld specimens containing carefully designed and implanted flaws were fabricated and inspected by qualified teams using techniques and procedures then-approved by PVRC.

In Table 1, we list the key attributes of the 12 PVRC weld specimens as documented by Hedden (1981) and subsequently updated to include the sectioning results of Yukawa (1981, 1983, 1984) and Saiga (1983, 1984b).

The availability of sectioning data for specimen 251J in early 1981 created an opportunity to answer two types of questions on NDE reliability. First of all, since specimen 251J was designed to contain 15 flaws of 4 different types, a comparison of the sectioning with the intended flaw location and sizing data could yield an estimate of the reliability of the flaw fabrication procedure.

Secondly, the round robin ultrasonic testing data of 251J as first analyzed by Buchanan (1976) under the assumption that the intended flaw location data were valid, need to be re-evaluated using the sectioning data to arrive at a more realistic estimate of the reliability of the 1968 ultrasonic testing procedure.

Following the release of the final sectioning data of specimen 251J by Yukawa (1984), the Center for Applied Mathematics of the National Bureau of Standards (NBS) undertook a two-year collaborative research project with PVRC to accomplish the following three goals:

(a) To conduct a flaw fabrication reliability analysis based on the final sectiong data of 251J and a classical analysis technique known as the analysis of variance (ANOVA) first introduced by Daniels (1939) and later discussed by many including Crump (1946), Eisenhart (1947), Hendricks (1951) and Mandel (1971).

(b) To re-analyze the round robin ultrasonic testing data of 251J (1968 PVRC procedure) by using the newly reported sectioning data rather than the old intended flaw data and by applying a new NDE reliability analysis technique recently proposed by Fong and Filliben (1986).

(c) To interpret and discuss the above two results not only for their intrinsic value in assessing the reliability of two procedures that were of the state of the art twenty years ago, but also for illuminating the value of an analysis technique in extracting information from round robin data that could assess and improve a class of test procedures involving sophisticated instrumentation and trained personnel such as the ultrasonic flaw detection system.

## 2. Overview of an NDE Data Analysis Methodology

The analysis technique mentioned in items (a) and (b) above and described in details in a companion paper (Fong and Filliben, 1986), was developed as part of a research project that grew out of a 1976 National Bureau of Standards (NBS) study on the structural integrity of hundreds of girth welds of the Trans-Alaska Oil Pipeline (Berger and Smith, 1976). The pipeline study was undertaken by NBS at the request of the U.S. Department of Transportation (DOT) in anticipation of the pipeline owner's request to waive then federal regulations on the non-acceptance of welds containing known defects. One of the main conclusions of the study reads as follows:

> "Defect dimensions can be determined with sufficient accuracy to be useful in the fracture mechanics analysis if the radiographs are made under carefully controlled conditions. If the radiographs are not made with close control, the accuracy of the defect sizes may not be sufficient to permit their use in establishing allowable defect sizes."

Since the field radiographs furnished by the pipeline owner were not made with close control, DOT concluded from the NBS study that there was not eough technical basis to grant the proposed waiver. All defective welds except three buried under a river crossing were required to be repaired at a cost close to one hundred million dollars.

An interpretation of the NBS study, as recently documented by Fong (1986a), identified two research needs that were not met in 1976 to support a stronger statement on the effectiveness of flaw sizing using field radiographs. Those two needs were:

(a) Database Need - A round robin pipeline weld flaw detection, location, and sizing database using field radiographs not necessarily made with close control but under a state-of-the-art procedure approved by the regulator.

(b) Analysis Need - An analysis methodology for converting those round robin data into defect detection, location and sizing reliability estimates applicable to new data compatible with the round robin database.

Following the 1976 study, the database need was interpreted to include ultrasonic test data to take advantage of the PVRC round robin program, and the analysis need was addressed in a number of NBS studies that were documented by Fong (1978), Fong and Dowling (1981), and Fong and Filliben (1986). With the aid of computer software in both the mainframe and the personal computer (PC) environment, an NDE data analysis methodology was designed to include the following four phases of computation:

| Phase | | Task | Remarks & References |
|---|---|---|---|
| I | - | Data Representation for Expert-Guided and Computer-Aided Screening. | Database Management; Graphics Software (Filliben, 1984). |
| II | - | Data Distribution Testing for both symmetric and asymmetric families. | (Filliben, 1969; Joiner & Rosenblatt, 1971; Filliben & Fong, 1984). |
| III | - | Data Analysis for Evaluating Effects of Certain Parameters in a Round Robin Test Program. | Analysis of Variance (Draper & Smith, 1981; Filliben, 1984). |
| IV | - | Estimation of Confidence Levels for a specific test procedure, coverage, and control parameter. | Tolerance Factors (Proschan, 1953; Beyer, 1966). |

To exercise the analysis methodology, a suitable set of round robin ultrasonic testing data for PVRC specimen 251J (Gillette and Smedley, 1968; White, 1968; Buchanan, 1976; Ruescher and Graber, 1981) of which the sectioning data (Yukawa, 1984) were available, was chosen. The results of this exercise and a discussion of their implications constitute the main body of this report.

## 3. Analysis of 251J Sectioning Data

PVRC specimen 251J was fabricated by welding two 11-inch thick plates of ASTM A-533-65, Grade B, low-alloy steel (80,000 psi tensil strength), using the submerged arc welding process. The dimensions of the specimen and a sketch of the relative locations of the 15 implanted flaws are given in Figs. 1 and 2. Of the 15 flaws, 5 were longitudinal cracks (LC), 5 cross cracks (CC), 3 long slag inclusions (LS) and 2 short slag inclusions (SS). The geometry of each flaw before sectioning was represented as a simple rectangular box with coordinates of its 6 planes given in Table 2.

As expected, the actual shape and location of each flaw after sectioning were quite complicated. In Fig. 3, we show the actual outline of a cross crack (flaw A) in two projections as first reported by Yukawa (1981). Assuming that the crack is a 2-dimensional curved surface embedded in a 3-dimensional space with each section in the x-z plane represented by a straight line in a preferred direction, a computer-aided graphical representation of the actual flaw A was accomplished by Fong (1982) as shown in Figs. 4 and 5.

To facilitate an in-depth analysis of the sectioning data versus the intended (Table 2), Yukawa (1983, 1984) reported a simplified representation of the sectioning data as shown in Table 3. Using an NBS-developed graphics-and-analysis-integrated software named DATAPLOT (Filliben, 1984), we show in Figs. 6 to 9 the box-type representation of each of the 15 flaws as found by sectioning. A comparison of the intended flaw location vs. sectioning data as projected on the y-z plane is shown in Fig. 10.

A visual inspection of Fig. 10 shows that the flaw fabrication procedure of the early 1960's was "not good." Our attempt here is to show that an analysis of the sectioning data can yield a quantitative statement on the effectiveness of the flaw fabrication procedure.

Let us consider a measure of the effectiveness of the procedure by defining a flaw size amplification factor (AF) equal to ratio of the actual maximum dimension of an implanted flaw to the intended maximum. In this case, we may consider the intended maximum dimension of each flaw as unity, and the amplification factor AF is the normalized variable for an analysis involving a sample of 15 data as shown below:

| | | | | | | |
|---|---|---|---|---|---|---|
| Cross Crack | A | E | I | | J | N |
| AF = | 2.133 | 2.667 | 2.467 | | 2.000 | 1.733 |
| Longit. Crack | C | D | H | | L | M |
| AF = | 1.575 | 1.650 | 2.750 | | 2.375 | 2.200 |
| Long Slag | B | G | O | Short Slag | F | K |
| AF = | 1.000 | 1.300 | 1.225 | AF = | 1.467 | 1.267 |

The analysis of the 15 maximum flaw dimension data (normalized) consists of four distinct steps as outlined below:

Step 1 Univariate Analysis

In this analysis, we consider a sample of 15 data which are equally representative of the quality of the flaw fabrication procedure. A histogram of the data is given in Fig. 11. The sample average (M) is 1.854, and the sample standard deviation (S) is 0.560. Assuming that the data follows a normal distribution, a plot based on the computed M and S is also given in Fig. 11.

Step 2 Distribution Testing

In Fig. 12, we present a probability plot of the data which appears to justify the assumption that the distribution is normal. Using a standard DATAPLOT routine based on Tukey's Lambda Test for families of symmetric distributions (Filliben, 1969; Joiner-Rosenblatt, 1971), we show in Fig. 13 that the correlation coefficient for the distribution to be normal is 0.98 which is close enough to unity to justify the normality assumption.

Step 3 Box Plot for Testing Homogeneity of Data

To examine whether the 15-data set is reasonably homogeneous even though it involves four types of flaws, we used a DATAPLOT routine called "boxplot" and display the results in Fig. 14. A visual inspection led us to conclude that there appears to be an effect due to flaw type with the fabrication procedure reasonably reliable for both types of slag inclusions and not so reliable otherwise.

Step 4 Analysis of Variance (ANOVA)

To determine the effect of flaw type, we conducted a one-way analysis of variance of the data set (see, e.g., Draper and Smith, 1981, pp. 423-454) by using a DATAPLOT routine called "anova." In addition to confirming that the grand standard deviation (S) equals 0.560, the analysis yielded an estimate of the standard deviation due to replication (SR) equal to 0.382.

To compute the standard deviation due to flaw type (S1), the following formula (see, e.g., Mandel, 1977) may be used if the number of replicas (denoted by m ) in each subgroup is contant:

$$(S1)^2 = (S)^2 - (SR)^2/m . \qquad (1)$$

For our data, m varies from 5 for the two types of cracks to 3 for long slags and 2 for short slags. If we denote the number of types by t, and m1, m2, ... mt, the number of data in each type, we introduce an equivalent number of replicas (mm) as the integer closest to and greater than the average of all the m's. In other words,

$$mm = \mathrm{INT}\,\{ (m1 + m2 + \ldots + mt)/t + 0.5 \}. \qquad (2)$$

For $t = 4$, $m1 = m2 = 5$, $m3 = 3$, $m4 = 2$, we found that the equivalent number of replicas for a constant-m ANOVA equals 4. Applying equation (1) with $m = 4$, $S = 0.560$, $SR = 0.382$, we obtained $S1 = 0.481$. We concluded that there was indeed a flaw type effect and the 15-data set was not homogeneous.

To incorporate the effect of flaw type, as represented by S1, into a new estimate of the variance of the data set, let us combine the standard deviations due to replication and the flaw type into a revised standard deviation, denoted by S2, as shown below:

$$(S2)^2 = (SR)^2 + (S1)^2 . \qquad (3)$$

For the 15-data set under consideration, S2 was found to be 0.614, which was about 10% higher than S (= 0.560) of the univariate analysis. A comparative plot of two normal distributions, one with and the other without estimating the so-called between-type variability, is given in Fig. 15.

## 4. Reliability of Flaw Fabrication

Since we have verified that the set of data for a 15-flaw and 4-type sample is normally distributed, we can estimate the upper and lower limits of the global mean and standard deviation of the amplification factor by using tables of values of the t- and chi-square distributions, respectively. Graphical plots of those limits for a range of confidence levels between 50% and 95% are given in Figs. 16 and 17.

Let us assume that one can estimate the reliability of flaw fabrication by concentrating on the variability of a single measure, namely, the amplification factor. Knowing the upper limits of that factor for either its global mean (Fig. 16) or global standard deviation (Fig. 17), is not enough to make a judgment of the fabrication process. Following Proschan (1953) and using the tables of tolerance factors K furnished by Beyer (1966, pp. 31-35) for various sample size N (2, 3,..., infinity) and four discrete values of the "coverage" or proportion P of the universe (P = 0.75, 0.90, 0.95, 0.99, 0.999), we can estimate the reliability of the flaw fabrication procedure as the probability or confidence level (CL) between 75% and 99% such that at least a proportion P of the distribution will be included between $M - K\,S$ and $M + K\,S$. Since Beyer's tables are for discrete values of CL (0.75, 0.90, 0.95, 0.99), we used an interpolation routine (Fong and Filliben, 1986) to obtain a continuous set of numbers for specific sample sizes (N = 15, 5) as shown in Figs. 17 and 18. We also reprint Beyer's tables for CL = 0.90, 0.95, and 0.99 in Tables 4, 5, and 6 to facilitate their applications for samples sizes different from 15 or 5.

Using $M = 1.854$ and $S = S2 = 0.614$ to account for the effect due to flaw type, we show in Fig. 20 the plots of reliability versus the upper limit $(M + K S)$ of the amplification factor for three values of coverage $(P = 0.90, 0.95, 0.99)$ as estimated from a 15-flaw sample. More specifically, the flaw fabrication procedure for the four flaw types considered in the 15-data sample is said to be 90% reliable in amplifying the maximum flaw dimension to at most 3.5 if the proportion of coverage is limited to 95%.

This above estimate may be used to accept or reject a procedure if a criterion is established compatible with the tolerance factor approach. For instance, if the acceptable maximum amplification factor is 2.0 and the acceptable reliability is 90% for a 95% coverage, then the above analysis yields the conclusion that the procedure is not acceptable.

The same analysis methodology can now be used to determine the reliability of the fabrication procedure for each type of flaws. For convenience, we choose to work with 3 types instead of 4 by combining the two types of slags into one such that the sample size of each type, i.e., cross cracks, longitudinal cracks, and slag inclusions, is 5, and the tolerance factor curves of Fig. 19 can be used in each case. The reliability plots for each flaw type can be found in Figs. 21, 22, and 23. The amplification factors for a 90%-reliability and 95%-coverage specification are found as follows:

| Type of Flaws | Upper Limit of Amplification Factors | Reference |
|---|---|---|
| All Flaw Types | 3.5 (90%-Reliability; 95%-Coverage) | Fig. 20. |
| Cross Cracks | 3.7 ( - do - ) | Fig. 21. |
| Longit. Cracks | 4.2 ( - do - ) | Fig. 22. |
| Slag Inclusions | 2.0 ( - do - ) | Fig. 23. |

The above result allows us to conclude that if the acceptance criterion is 2.0, the fabrication procedure passes for slag inclusions but not for cross cracks or longitudinal cracks.

## 5. Verification of Round Robin UT-1968 Data

We now report the results of the second portion of this study, namely, the re-evaluation and reliability modeling of the 1968-procedure of ultrasonic detection of flaws in a thick-section steel weld. The study involved the use of the 5-team round robin data of specimen 251J (Gillette and Smedley, 1968; White, 1968) and the 1984 sectioning data by Yukawa (1984, 1986). The analysis methodology (Fong and Filliben, 1986) is also based on the application of ANOVA and the use of tolerance factor tables.

In Tables 7 through 11, we reprint the ultrasonic test (1968-procedure) data (UT-1968) for teams A, B, C, D, and F, respectively. We show in Figs. 24 through 28 the y-z projections of the data as a pre-analysis quality check.

In Fig. 24, we observed that eight of the 18 indications by team A fell outside the physical bounds of the specimen. The data were sent to the PVRC Subcommittee on NDE of Pressure Components for re-examination, and a revised set by Hedden (1984a) as shown in Table 12 and Fig. 29 was used for further analysis. Following a closer reading of more subcommittee documents, Hedden (1984b) further revised the team A data as shown in Table 13 and Fig. 30. A visual comparison of Figs. 24, 29, and 30 shows the importance of an expert-assisted and computer-aided data quality check before any major step of analysis is undertaken.

An examination of Figs. 25 and 26 for the 4-indication data set of team B and the 14-indication data set of team C, respectively, led us to conclude that both sets were acceptable. Questions were raised with the PVRC Subcommittee on NDE regarding the acceptability of data sets for teams D and F (see Figs. 27 and 28), and were not fully resolved by a communication due to Hedden (1985). As a first step toward the application of the analysis methodology to PVRC UT-1968 data, it was proposed by the author and approved by PVRC that the remaining portion of this study be limited to the use of the full data sets of teams A, B, and C for studying reliability, and one specific indication from the data set of team D for discussing shortcomings of the analysis methodology.

## 6. Analysis of Individual Team UT-1968 Data

To emulate the decision-making process of matching a UT indication with the actual locations of the 15 implanted flaws, we initiated the design and implementation of a detection-analysis software (Fong and Filliben, 1986), where the database management capability of a personal computer (PC), and the analysis capability of a mainframe or mini-computer using DATAPLOT (Filliben, 1984), were integrated. The results of the analysis for three typical indications of team A, one of team B, two of team C, and one of team D, are given in Figs. 31 through 37. The analysis may be described as a two-part exercise where the first part deals with each indication as reported and is accomplished in three steps as shown below:

Step 1 Center-to-Center Distance Computation

For this step, we convert all box-type data for the 15 implanted flaws into centroid and half-length data to facilitate the computation of the center-to-center distances (CD) between an indication and each of the 15 implanted flaws. Those fifteen CD's are then ordered in an ascending sequence for a comparison with a set of threshold values.

Step 2 Identification of Flaws Detected vs. Threshold

Consider an ascending sequence of flaw detection thresholds between 1/4 and 3.0 inches in increments of 1/4 inch. For each value of the detection threshold and each indication, identify the flaw or flaws whose center-to-center distance(s) are equal or less than the threshold. A new sequence of positive integers is then found to characterize the detection capability of the indication as a function of the detection threshold.

Step 3 Graphical and Text Representation of Each Indication

Plot the number of flaws detected versus the detection threshold and display the name of the nearest flaw detected, the center-to-center distance, the ratio of the maximum dimension of actual flaw to that of the detected one (size factor), and the maximum DAC value reported for the indication. Typical examples of such display are given in Figs. 31-37.

By collecting the results of the analysis for each of the indications reported, we can assess the capability of each team by introducing two detection probabilities and one activity measure, each as a function of the detection threshold, as shown below:

(a) True-Call Probability (TCP) - For each detection threshold and each indication, the above analysis allows us to answer the question whether any flaw has been identified. If the answer is yes, we assign 1 to the indication as a true call. Otherwise, we assign 0 to show it is a false call. The true-call probability (TCP) is defined as the ratio of the total number of true calls registered to the total number of indications reported. If an indication identifies more than one flaw, as in the case of Fig. 31 for threshold equal to 2.25 or greater, the true call count is still 1.

This measure allows us to define a false-call probability (FCP) by the expression FCP = 1 - TCP. Results for teams A, B, C, are reported in Figs. 38-40. A visual inspection allows one to conclude that a 2-inch threshold is enough for all 3 teams to claim a 100% TCP or 0% FCP.

(b) Flaw Detection Probability (FDP) - Among the true calls, it happens that some of the flaws were identified more than once. The purpose of introducing FDP is to eliminate the duplicate calls by counting exactly how many flaws the team has found. Thus we define the flaw detection probability, FDP, as the total number of distinct flaws detected to the total number of flaws implanted. Again, an examination of Figs. 38-40 shows that a team B did well on the TCP measure, but poorly on this measure.

(c) Activity Index (AI) - A composite index that measures a team's activity rather than efficiency is to define an activity index equal to the total number of true calls divided by the total number of implanted flaws. In Figs. 41-43, we display the results for teams A, B, C, and for different types of flaws to see if there is a flaw type effect in the ease of detectability. The answer appears to be negative, and can be justified quantitatively via an analysis of variance as shown in the next section.

## 7. Analysis of 3-Team UT-1968 Data

One of the main difficulties in assessing the reliability of a complex test procedure such as NDE is the requirement for a large quantity of data normally unavailable or economically unfeasible. The lack of an *a priori* knowledge of the distribution or variability of many instrument and human factors creates a barrier for a credible reliability analysis based on a small amount of round robin data.

On the other hand, if we can show that the underlying distribution of a "control variable" is normal or close to, a combination of the powerful technique of the analysis of variance (ANOVA) and the concept of tolerance factors can be applied even though the quantity of data is "small." An example of this has been presented earlier in assessing the reliability of a flaw fabrication procedure (Section 4). In this section, we shall present an analysis of the 3-team UT-1968 data by first choosing a control variable, then testing its underlying distribution, and finally applying the ANOVA to evaluate between-team, flaw-type, and DAC effects on the 3-team data.

The variable we choose to work with is the smallest detection threshold (DT) for new and distinct flaws to be detected. This variable has the practical property that the height of its histogram should be zero at DT = 0 and DT = DTMAX, where DTMAX equals some large number. The question to be answered is whether the distribution of the variable using data between DT = 0 and DT = DTMAX is close to normal. If that were the case, we can apply the analysis methodology to yield some information on the reliability of the NDE procedure. If not, we have no alternative but to seek more data and an alternate variable.

A histogram of the data for the above-mentioned control variable based on the analysis of the last section is given in Fig. 44. The results of the analysis for all three teams have been combined to yield a data set of sample size equal to 28. Using DATAPLOT routines for testing family of symmetric distributions (Fig. 45), Weibull distributions (Figs. 46-47), and Extreme Value distributions (Fig. 48), we found that the distribution of the control variable is reasonably normal.

We then apply the DATAPLOT routine of the analysis of variance to answer the following three questions:

(a) Is there a between-team effect in the 3-team round robin data set?

(b) Is there a flaw-type effect in the same data set?

(c) Is there a DAC effect in the same data set?

The results of the one-way ANOVA for each of the above questions are given in Figs. 49-51. In each case, no effect was found in the 28-point data set. The answer for question (b) seemed reasonable since we have already observed the lack of a flaw-type effect in the results of Section 6.

## 8. Reliability of UT-1968 Procedure

To assess the reliability of the UT-1968 procedure, we follow the approach used in Section 4 by first obtaining a set of curves for the tolerance factor K for sample size equal to 28 (Fig. 52), and then plotting the upper tolerance limits M + K S for the sample of 28 data points with M = 1.36 and S = 0.454. The result is shown in Fig. 53. The following may be used to quantify the reliability of the UT-1968 procedure:

| Case | Coverage | Reliability | Det. Thresh. Tol. Limit (in.) |
|---|---|---|---|
| I | 90 % | 90 % | 2.3 |
| II | 90 % | 95 % | 2.35 |
| III | 95 % | 95 % | 2.55 |

If the prescribed detection threshold is 2 in. for 90% coverage and 95% reliability, then the procedure fails as shown in Case I even though the sample average (= 1.36 in.) is well within the prescribed threshold. The result could be used to establish a base-line for the UT procedure such that any change in the procedure could be assessed through a new round robin program by observing any changes in the upper tolerance limits.

## 9. Discussion & Future Work

We have presented two sets of results in this study. The first is on the reliability of a flaw fabrication procedure for a thick-section steel weld specimen. To our knowledge, this is the first time such result has ever been published. The use of the one-way analysis of variance technique to evaluate the reliability of the procedure for different types of flaws is both interesting and instructive. A more thorough discussion of the results of Section 4 appears in a companion paper (Fong, 1986b).

The second set of results applies to an outdated ultrasonic test procedure (UT-1968). The negative results are not surprising, since in those days the detection of flaws by NDE was more an art than an engineering discipline. The significance of the results lies more in the analysis approach and newly introduced concepts than in the conclusion that UT-1968 is unsatisfactory. A comparison of this study with an earlier one by Buchanan (1976) shows that our analysis methodology has yielded quantitative answers to at least five new questions on the UT-1968 procedure:

(a) What is the false call probability of each team?
(b) Is there a between-team effect?
(c) Is there a flaw-type effect?
(d) Is there a DAC effect?
(e) What is the detection reliability of the UT procedure?

In addition, the analysis methodology requires a data quality check which altered the data of team A and excluded the data of teams D and F on technical grounds that are considered essential for an automated data analysis and decision-making exercise.

The interaction between PVRC as the data expert and NBS as the analyst and expert-system researcher turned out to be one of the key ingredients in a successful completion of this study. The design and implementation of the PC-based and mainframe-linked prototype software for NDE data analysis is part of an on-going NBS research project known as DATAX (Fong, Cramer, and Redmiles, 1984; Fong, 1986a). It is hoped that similar applications of the prototype software in other engineering fields would be equally successful.

As hinted in the introduction, this study has the dual role of providing some new answers to a 20-year-old problem and proving the feasibility of an analysis methodology that is still in its prototype stage. Having succeeded in answering a small number of questions on NDE reliability and demonstrating the usefulness of the methodology, we suggest that additional work could be undertaken to update old studies and assess current NDE procedures. In particular, we like to list the following as a sample of future work that needs to be completed to achieve the goals set by PVRC:

(i) What is the location reliability of the procedure UT-1968?

(ii) What is the sizing reliability of the procedure UT-1968?

(iii) What are the reliabilities of procedures used in detecting other PVRC specimens with known sectioning data (Adamonis & Hughes, 1979; PISC-I, 1979a; Saiga, 1983; Saiga, 1984b)?

(iv) Is there a human factor effect (see Behravesh and Dau, 1986)?

(v) Is the NDE reliability results of this study compatible with similar conclusions in the literature (Lewis et al, 1978; Johnson et al, 1979; PISC-I, 1979b; Watkins et al, 1982; Saiga, 1984a and 1984c; PISC-II, 1985; etc.)?

## 10. Conclusion

The analysis of the 1984 sectioning data of PVRC specimen 251J shows that the flaw fabrication procedure is dimensionally unsatisfactory for cross cracks and longitudinal cracks, but is "reliable" for slag inclusions if a size amplification factor of 2 is acceptable.

The detection threshold for zero false call probability is 2.0 inches for teams A, B, and C using an ultrasonic test procedure then in use in 1968. The procedure, however, is less than 90% reliable if the prescribed threshold for a true flaw to be in the neighborhood of an indication is 2.0 inches (center-to-center).

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| | |
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LIST OF TABLES

Table 1 - List of PVRC Weld Specimens for A Series of Round Robin Flaw Detection Program using Ultrasonic Testing (1966- ).

```
Begin R:base 4000 Version 1.01 MSDOS Serial # ########
For the IBM Personal Computer
Copyright 1983 by Microrim, Inc.

For assistance type "HELP", for Prompt mode type "PROMPT"
R>
open a:pvrc
 Database exists
listrel

     Relations in the Database pvrc

     platgeom 'weldgeom  temp2     mat       general   temp1

listrel general

     Relation: general
     Read Password: NO
     Modify Password: NO

              Attributes
       # Name     Type     Length         Key
       1 specimen TEXT       5 characters
       2 fabrictr TEXT      16 characters
       3 thicknes TEXT      16 characters
       4 flawplan TEXT      16 characters
       5 sect'ner TEXT      16 characters

     Current number of rows:     12

select all from general
 specimen fabrictr         thicknes         flawplan         sect'ner
 -------- ---------------- ---------------- ---------------- ----------------
 251-J    Combustion Eng.  11 in. (butt, s) 15 (var. types)  Yukawa (1984)
 252-J    Combustion Eng.   8 in. (butt, e)  3 areas (var.)  ---
 253-J    Combustion Eng.  11 in. (f-nz, s) 20 (var. types)  ---
 254-J    Combustion Eng.  10 in. (f-nz, s) 25 (var. types)  ---
 201      Chicago B & I     8 in. (butt, m) 10 (var. types)  Adamonis (1979)
 202      Chicago B & I     8 in. (butt, mc  9 (var. types)  Saiga (1983)
 203      Chicago B & I     8 in. (f-nz, m)  9 (var. types)  Saiga (1984b)
 204      Chicago B & I     8 in. (f-nz. m)  9 (var. types)  PISC-I (1979)
 50-52    Babcock & Wilcox 11 in. (butt, e)  gross cracks    PISC-I (1979)
 51-53    Babcock & Wilcox  8 in. (butt, s)  gross cracks    PISC-I (1979)
 155      Babcock & Wilcox 8.75" (f-nz, sc   4 (all types)   ---
 156      Babcock & Wilcox  5 in. (c-nz, s)  3 areas (var.)  ---
```

Legend:
- c-nz = cast nozzle
- e = electroslag weld
- f-nz = forged nozzle
- m = manual metal arc weld
- mc = manual metal arc weld with cladding
- s = submerged arc weld
- sc = submerged arc weld with cladding

Table 2 - Intended Location Coordinates of 15 Flaws Implanted in PVRC Specimen 251J (LC = Longitudinal Crack; CC = Cross Crack; LS = Long Slag; and SS = Short Slag). After Buchanan (1976).

```
Begin R:base 4000 Version 1.01 MSDOS Serial # ########
For the IBM Personal Computer
Copyright 1983 by Microrim, Inc.

For assistance type "HELP", for Prompt mode type "PROMPT"
R>
open a:251-J
 Database exists
listrel

     Relations in the Database 251-J

     sec-type  sec-ty-s  int-type  int-ty-s  sec-1-cc  sec-2-lc
     int-15    sec-15    sec-3-ls  sec-4-ss  int-1-cc  int-2-lc
     int-3-ls  int-4-ss

listrel int-15

     Relation: int-15
     Read Password: NO
     Modify Password: NO

               Attributes
       # Name     Type      Length         Key
       1 flawname TEXT        8 characters
       2 x1(int)  REAL        1 value(s)
       3 x2(int)  REAL        1 value(s)
       4 y1(int)  REAL        1 value(s)
       5 y2(int)  REAL        1 value(s)
       6 z1(int)  REAL        1 value(s)
       7 z2(int)  REAL        1 value(s)

     Current number of rows:     15

select all from int-15
 flawname x1(int)  x2(int)  y1(int)  y2(int)  z1(int)  z2(int)
 -------- -------- -------- -------- -------- -------- --------
 A  (CC)   25.5000  26.2500  2.98000  3.02000  0.98000  1.02000
 B  (LS)   26.2300  26.2700  16.0000  18.0000  0.98000  1.02000
 C  (LC)   26.2300  26.2700  30.0000  32.0000  0.98000  1.02000
 D  (LC)   24.9800  25.0200  2.00000  4.00000  2.73000  2.77000
 E  (CC)   25.0000  25.7500  16.9800  17.0200  2.73000  2.77000
 F  (SS)   24.9800  25.0200  30.6500  31.4000  2.73000  2.77000
 G  (LS)   26.2300  26.2700  2.00000  4.00000  5.48000  5.52000
 H  (LC)   26.2300  26.2700  16.0000  18.0000  5.48000  5.52000
 I  (CC)   25.5000  26.2500  30.9800  31.0200  5.48000  5.52000
 J  (CC)   25.0000  25.7500  2.98000  3.02000  8.23000  8.27000
 K  (SS)   25.0000  25.7500  16.9800  17.0200  8.23000  8.27000
 L  (LC)   24.9800  25.0200  30.0000  32.0000  8.23000  8.27000
 M  (LC)   26.2300  26.2700  2.00000  4.00000  9.98000  10.0200
 N  (CC)   25.5000  26.2500  16.9800  17.0200  9.98000  10.0200
 O  (LS)   26.2300  26.2700  30.0000  32.0000  9.98000  10.0200
```

Table 3 - Actual Location Coordinates of 15 Flaws in PVRC Specimen 251J as determined by Sectioning (Yukawa, 1984). (LC = Longitudinal Crack; CC = Cross Crack; LS = Long Slag; and SS = Short Slag.)

```
Begin R:base 4000 Version 1.01 MSDOS Serial # ########
For the IBM Personal Computer
Copyright 1983 by Microrim, Inc.

For assistance type "HELP", for Prompt mode type "PROMPT"
R>
open a:251-J
 Database exists
listrel

     Relations in the Database 251-J

     sec-type  sec-ty-s  int-type  int-ty-s  sec-1-cc  sec-2-lc
     int-15    sec-15    sec-3-ls  sec-4-ss  int-1-cc  int-2-lc
     int-3-ls  int-4-ss

listrel sec-15

     Relation: sec-15
     Read Password: NO
     Modify Password: NO

               Attributes
       # Name     Type      Length          Key
       1 flawname TEXT       8 characters
       2 x1(sect) REAL       1 value(s)
       3 x2(sect) REAL       1 value(s)
       4 y1(sect) REAL       1 value(s)
       5 y2(sect) REAL       1 value(s)
       6 z1(sect) REAL       1 value(s)
       7 z2(sect) REAL       1 value(s)

     Current number of rows:     15

select all from sec-15
 flawname x1(sect) x2(sect) y1(sect) y2(sect) z1(sect) z2(sect)
 -------- -------- -------- -------- -------- -------- --------
 A  (CC)   26.1000  26.4500  2.60000  4.20000  0.95000  1.30000
 B  (LS)   26.3000  26.4500  16.1000  18.1000  0.60000  1.15000
 C  (LC)   26.0000  26.4500  30.0500  33.2000  0.65000  1.20000
 D  (LC)   25.1500  25.6500  2.20000  5.50000  2.35000  3.10000
 E  (CC)   25.1500  25.4500  17.1000  19.1000  2.85000  3.15000
 F  (SS)   25.1000  25.2500  30.7000  31.8000  1.90000  2.75000
 G  (LS)   26.2000  26.4000  2.20000  4.80000  4.70000  5.45000
 H  (LC)   25.6500  26.3500  16.1000  21.6000  4.95000  5.75000
 I  (CC)   26.0000  26.3500  30.2000  32.0500  5.00000  5.65000
 J  (CC)   25.1000  25.4500  3.05000  4.55000  7.70000  8.30000
 K  (SS)   25.1000  25.4500  17.1500  18.1000  8.00000  8.25000
 L  (LC)   25.1000  25.7500  29.1000  33.8500  7.60000  8.10000
 M  (LC)   25.9500  26.3000  1.05000  5.45000  9.25000  9.85000
 N  (CC)   25.3000  26.3000  16.8000  18.1000  9.35000  9.75000
 O  (LS)   25.9500  26.2500  29.7500  32.2000  9.55000  10.3000
```

Table 4 - Tolerance Factors K for Normal Distributions of Data of Sample Size N and for 90% Confidence that at least P % of the Population will be included in the interval (M - KS) and (M + KS), where M = estimated mean, and S = est. s.d. After Beyer (1966).

*Normal Distribution*

**TOLERANCE FACTORS FOR NORMAL DISTRIBUTIONS**

| | λ = 0.90 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| N \ P | 0.75 | 0.90 | 0.95 | 0.99 | 0.999 | N \ P | 0.75 | 0.90 | 0.95 | 0.99 | 0.999 |
| 2 | 11.407 | 15.978 | 18.800 | 24.167 | 30.227 | 55 | 1.329 | 1.901 | 2.265 | 2.976 | 3.801 |
| 3 | 4.132 | 5.847 | 6.919 | 8.974 | 11.309 | 60 | 1.320 | 1.887 | 2.248 | 2.955 | 3.774 |
| 4 | 2.932 | 4.166 | 4.943 | 6.440 | 8.149 | 65 | 1.312 | 1.875 | 2.235 | 2.937 | 3.751 |
| 5 | 2.454 | 3.494 | 4.152 | 5.423 | 6.879 | 70 | 1.304 | 1.865 | 2.222 | 2.920 | 3.730 |
| 6 | 2.196 | 3.131 | 3.723 | 4.870 | 6.188 | 75 | 1.298 | 1.856 | 2.211 | 2.906 | 3.712 |
| 7 | 2.034 | 2.902 | 3.452 | 4.521 | 5.750 | 80 | 1.292 | 1.848 | 2.202 | 2.894 | 3.696 |
| 8 | 1.921 | 2.743 | 3.264 | 4.278 | 5.446 | 85 | 1.287 | 1.841 | 2.193 | 2.882 | 3.682 |
| 9 | 1.839 | 2.626 | 3.125 | 4.098 | 5.220 | 90 | 1.283 | 1.834 | 2.185 | 2.872 | 3.669 |
| 10 | 1.775 | 2.535 | 3.018 | 3.959 | 5.046 | 95 | 1.278 | 1.828 | 2.178 | 2.863 | 3.657 |
| 11 | 1.724 | 2.463 | 2.933 | 3.849 | 4.906 | 100 | 1.275 | 1.822 | 2.172 | 2.854 | 3.646 |
| 12 | 1.683 | 2.404 | 2.863 | 3.758 | 4.792 | 110 | 1.268 | 1.813 | 2.160 | 2.839 | 3.626 |
| 13 | 1.648 | 2.355 | 2.805 | 3.682 | 4.697 | 120 | 1.262 | 1.804 | 2.150 | 2.826 | 3.610 |
| 14 | 1.619 | 2.314 | 2.756 | 3.618 | 4.615 | 130 | 1.257 | 1.797 | 2.141 | 2.814 | 3.595 |
| 15 | 1.594 | 2.278 | 2.713 | 3.562 | 4.545 | 140 | 1.252 | 1.791 | 2.134 | 2.804 | 3.582 |
| 16 | 1.572 | 2.246 | 2.676 | 3.514 | 4.484 | 150 | 1.248 | 1.785 | 2.127 | 2.795 | 3.571 |
| 17 | 1.552 | 2.219 | 2.643 | 3.471 | 4.430 | 160 | 1.245 | 1.780 | 2.121 | 2.787 | 3.561 |
| 18 | 1.535 | 2.194 | 2.614 | 3.433 | 4.382 | 170 | 1.242 | 1.775 | 2.116 | 2.780 | 3.552 |
| 19 | 1.520 | 2.172 | 2.588 | 3.399 | 4.339 | 180 | 1.239 | 1.771 | 2.111 | 2.774 | 3.543 |
| 20 | 1.506 | 2.152 | 2.564 | 3.368 | 4.300 | 190 | 1.236 | 1.767 | 2.106 | 2.768 | 3.536 |
| 21 | 1.493 | 2.135 | 2.543 | 3.340 | 4.264 | 200 | 1.234 | 1.764 | 2.102 | 2.762 | 3.429 |
| 22 | 1.482 | 2.118 | 2.524 | 3.315 | 4.232 | 250 | 1.224 | 1.750 | 2.085 | 2.740 | 3.501 |
| 23 | 1.471 | 2.103 | 2.506 | 3.292 | 4.203 | 300 | 1.217 | 1.740 | 2.073 | 2.725 | 3.481 |
| 24 | 1.462 | 2.089 | 2.489 | 3.270 | 4.176 | 400 | 1.207 | 1.726 | 2.057 | 2.703 | 3.453 |
| 25 | 1.453 | 2.077 | 2.474 | 3.251 | 4.151 | 500 | 1.201 | 1.717 | 2.046 | 2.689 | 3.434 |
| 26 | 1.444 | 2.065 | 2.460 | 3.232 | 4.127 | 600 | 1.196 | 1.710 | 2.038 | 2.678 | 3.421 |
| 27 | 1.437 | 2.054 | 2.447 | 3.215 | 4.106 | 700 | 1.192 | 1.705 | 2.032 | 2.670 | 3.411 |
| 30 | 1.417 | 2.025 | 2.413 | 3.170 | 4.049 | 800 | 1.189 | 1.701 | 2.027 | 2.663 | 3.402 |
| 35 | 1.390 | 1.988 | 2.368 | 3.112 | 3.974 | 900 | 1.187 | 1.697 | 2.023 | 2.658 | 3.396 |
| 40 | 1.370 | 1.959 | 2.334 | 3.066 | 3.917 | 1000 | 1.185 | 1.695 | 2.019 | 2.654 | 3.390 |
| 45 | 1.354 | 1.935 | 2.306 | 3.030 | 3.871 | $\infty$ | 1.150 | 1.645 | 1.960 | 2.576 | 3.291 |
| 50 | 1.340 | 1.916 | 2.284 | 3.001 | 3.833 | | | | | | |

Table 5 - Tolerance Factors K for Normal Distributions of Data of Sample Size N and for 95% Confidence that at least P % of the Population will be included in the interval (M - KS) and (M + KS), where M = estimated mean, and S = est. s.d. After Beyer (1966).

*Normal Distribution*

**TOLERANCE FACTORS FOR NORMAL DISTRIBUTIONS**

| | $\lambda = 0.95$ | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| N \ P | 0.75 | 0.90 | 0.95 | 0.99 | 0.999 | N \ P | 0.75 | 0.90 | 0.95 | 0.99 | 0.999 |
| 2 | 22.858 | 32.019 | 37.674 | 48.430 | 60.573 | 55 | 1.382 | 1.976 | 2.354 | 3.094 | 3.951 |
| 3 | 5.922 | 8.380 | 9.916 | 12.861 | 16.208 | 60 | 1.369 | 1.958 | 2.333 | 3.066 | 3.916 |
| 4 | 3.779 | 5.369 | 6.370 | 8.299 | 10.502 | 65 | 1.359 | 1.943 | 2.315 | 3.042 | 3.886 |
| 5 | 3.002 | 4.275 | 5.079 | 6.634 | 8.415 | 70 | 1.349 | 1.929 | 2.299 | 3.021 | 3.859 |
| 6 | 2.604 | 3.712 | 4.414 | 5.775 | 7.337 | 75 | 1.341 | 1.917 | 2.285 | 3.002 | 3.835 |
| 7 | 2.361 | 3.369 | 4.007 | 5.248 | 6.676 | 80 | 1.334 | 1.907 | 2.272 | 2.986 | 3.814 |
| 8 | 2.197 | 3.136 | 3.732 | 4.891 | 6.226 | 85 | 1.327 | 1.897 | 2.261 | 2.971 | 3.795 |
| 9 | 2.078 | 2.967 | 3.532 | 4.631 | 5.899 | 90 | 1.321 | 1.889 | 2.251 | 2.958 | 3.778 |
| 10 | 1.987 | 2.839 | 3.379 | 4.433 | 5.649 | 95 | 1.315 | 1.881 | 2.241 | 2.945 | 3.763 |
| 11 | 1.916 | 2.737 | 3.259 | 4.277 | 5.452 | 100 | 1.311 | 1.874 | 2.233 | 2.934 | 3.748 |
| 12 | 1.858 | 2.655 | 3.162 | 4.150 | 5.291 | 110 | 1.302 | 1.861 | 2.218 | 2.915 | 3.723 |
| 13 | 1.810 | 2.587 | 3.081 | 4.044 | 5.158 | 120 | 1.294 | 1.850 | 2.205 | 2.898 | 3.702 |
| 14 | 1.770 | 2.529 | 3.012 | 3.955 | 5.045 | 130 | 1.288 | 1.841 | 2.194 | 2.883 | 3.683 |
| 15 | 1.735 | 2.480 | 2.954 | 3.878 | 4.949 | 140 | 1.282 | 1.833 | 2.184 | 2.870 | 3.666 |
| 16 | 1.705 | 2.437 | 2.903 | 3.812 | 4.865 | 150 | 1.277 | 1.825 | 1.175 | 2.859 | 3.652 |
| 17 | 1.679 | 2.400 | 2.858 | 3.754 | 4.791 | 160 | 1.272 | 1.819 | 2.167 | 2.848 | 3.638 |
| 18 | 1.655 | 2.366 | 2.819 | 3.702 | 4.725 | 170 | 1.268 | 1.813 | 2.160 | 2.839 | 3.627 |
| 19 | 1.635 | 2.337 | 2.784 | 3.656 | 4.667 | 180 | 1.264 | 1.808 | 2.154 | 2.831 | 3.616 |
| 20 | 1.616 | 2.310 | 2.752 | 3.615 | 4.614 | 190 | 1.261 | 1.803 | 2.148 | 2.823 | 3.606 |
| 21 | 1.599 | 2.286 | 2.723 | 3.577 | 4.567 | 200 | 1.258 | 1.798 | 2.143 | 2.816 | 3.597 |
| 22 | 1.584 | 2.264 | 2.697 | 3.543 | 4.523 | 250 | 1.245 | 1.780 | 2.121 | 2.788 | 3.561 |
| 23 | 1.570 | 2.244 | 2.673 | 3.512 | 4.484 | 300 | 1.236 | 1.767 | 2.106 | 2.767 | 3.535 |
| 24 | 1.557 | 2.225 | 2.651 | 3.483 | 4.447 | 400 | 1.223 | 1.749 | 2.084 | 2.739 | 3.499 |
| 25 | 1.545 | 2.208 | 2.631 | 3.457 | 4.413 | 500 | 1.215 | 1.737 | 2.070 | 2.721 | 3.475 |
| 26 | 1.534 | 2.193 | 2.612 | 3.432 | 4.382 | 600 | 1.209 | 1.729 | 2.060 | 2.707 | 3.458 |
| 27 | 1.523 | 2.178 | 2.595 | 3.409 | 4.353 | 700 | 1.204 | 1.722 | 2.052 | 2.697 | 3.445 |
| 30 | 1.497 | 2.140 | 2.549 | 3.350 | 4.278 | 800 | 1.201 | 1.717 | 2.046 | 2.688 | 3.434 |
| 35 | 1.462 | 2.090 | 2.490 | 3.272 | 4.179 | 900 | 1.198 | 1.712 | 2.040 | 2.682 | 3.426 |
| 40 | 1.435 | 2.052 | 2.445 | 3.213 | 4.104 | 1000 | 1.195 | 1.709 | 2.036 | 2.676 | 3.418 |
| 45 | 1.414 | 2.021 | 2.408 | 3.165 | 4.042 | $\infty$ | 1.150 | 1.645 | 1.960 | 2.576 | 3.291 |
| 50 | 1.396 | 1.996 | 2.379 | 3.126 | 3.993 | | | | | | |

Table 6 - Tolerance Factors K for Normal Distributions of Data of Sample Size N and for 99% Confidence that at least P % of the Population will be included in the interval (M - KS) and (M + KS), where M = estimated mean, and S = est. s.d. After Beyer (1966).

***Normal Distribution***

**TOLERANCE FACTORS FOR NORMAL DISTRIBUTIONS**

| | $\lambda = 0.99$ | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| N \ P | 0.75 | 0.90 | 0.95 | 0.99 | 0.999 | N \ P | 0.75 | 0.90 | 0.95 | 0.99 | 0.999 |
| 2 | 114.363 | 160.193 | 188.491 | 242.300 | 303.054 | 55 | 1.490 | 2.130 | 2.538 | 3.335 | 4.260 |
| 3 | 13.378 | 18.930 | 22.401 | 29.055 | 36.616 | 60 | 1.471 | 2.103 | 2.506 | 3.293 | 4.206 |
| 4 | 6.614 | 9.398 | 11.150 | 14.527 | 18.383 | 65 | 1.455 | 2.080 | 2.478 | 3.257 | 4.160 |
| 5 | 4.643 | 6.612 | 7.855 | 10.260 | 13.015 | 70 | 1.440 | 2.060 | 2.454 | 3.225 | 4.120 |
| 6 | 3.743 | 5.337 | 6.345 | 8.301 | 10.548 | 75 | 1.428 | 2.042 | 2.433 | 3.197 | 4.084 |
| 7 | 3.233 | 4.613 | 5.488 | 7.187 | 9.142 | 80 | 1.417 | 2.026 | 2.414 | 3.173 | 4.053 |
| 8 | 2.905 | 4.147 | 4.936 | 6.468 | 8.234 | 85 | 1.407 | 2.012 | 2.397 | 3.150 | 4.024 |
| 9 | 2.677 | 3.822 | 4.550 | 5.966 | 7.600 | 90 | 1.398 | 1.999 | 2.382 | 3.130 | 3.999 |
| 10 | 2.508 | 3.582 | 4.265 | 5.594 | 7.129 | 95 | 1.390 | 1.987 | 2.368 | 3.112 | 3.976 |
| 11 | 2.378 | 3.397 | 4.045 | 5.308 | 6.766 | 100 | 1.383 | 1.977 | 2.355 | 3.096 | 3.954 |
| 12 | 2.274 | 3.250 | 3.870 | 5.079 | 6.477 | 110 | 1.369 | 1.958 | 2.333 | 3.066 | 3.917 |
| 13 | 2.190 | 3.130 | 3.727 | 4.893 | 6.240 | 120 | 1.358 | 1.942 | 2.314 | 3.041 | 3.885 |
| 14 | 2.120 | 3.029 | 3.608 | 4.737 | 6.043 | 130 | 1.349 | 1.928 | 2.298 | 3.019 | 3.857 |
| 15 | 2.060 | 2.945 | 3.507 | 4.605 | 5.876 | 140 | 1.340 | 1.916 | 2.283 | 3.000 | 3.833 |
| 16 | 2.009 | 2.872 | 3.421 | 4.492 | 5.732 | 150 | 1.332 | 1.905 | 2.270 | 2.983 | 3.811 |
| 17 | 1.965 | 2.808 | 3.345 | 4.393 | 5.607 | 160 | 1.326 | 1.896 | 2.259 | 2.968 | 3.792 |
| 18 | 1.926 | 2.753 | 3.279 | 4.307 | 5.497 | 170 | 1.320 | 1.887 | 2.248 | 2.955 | 3.774 |
| 19 | 1.891 | 2.703 | 3.221 | 4.230 | 5.399 | 180 | 1.314 | 1.879 | 2.239 | 2.942 | 3.759 |
| 20 | 1.860 | 2.659 | 3.168 | 4.161 | 5.312 | 190 | 1.309 | 1.872 | 2.230 | 2.931 | 3.744 |
| 21 | 1.833 | 2.620 | 3.121 | 4.100 | 5.234 | 200 | 1.304 | 1.865 | 2.222 | 2.921 | 3.731 |
| 22 | 1.808 | 2.584 | 3.078 | 4.044 | 5.163 | 250 | 1.286 | 1.839 | 2.191 | 2.880 | 3.678 |
| 23 | 1.785 | 2.551 | 3.040 | 3.993 | 5.098 | 300 | 1.273 | 1.820 | 2.169 | 2.850 | 3.641 |
| 24 | 1.764 | 2.522 | 3.004 | 3.947 | 5.039 | 400 | 1.255 | 1.794 | 2.138 | 2.809 | 3.589 |
| 25 | 1.745 | 2.494 | 2.972 | 3.904 | 4.985 | 500 | 1.243 | 1.777 | 2.117 | 2.783 | 3.555 |
| 26 | 1.727 | 2.469 | 2.941 | 3.865 | 4.935 | 600 | 1.234 | 1.764 | 2.102 | 2.763 | 3.530 |
| 27 | 1.711 | 2.446 | 2.914 | 3.828 | 4.888 | 700 | 1.227 | 1.755 | 2.091 | 2.748 | 3.511 |
| 30 | 1.668 | 2.385 | 2.841 | 3.733 | 4.768 | 800 | 1.222 | 1.747 | 2.082 | 2.736 | 3.495 |
| 35 | 1.613 | 2.306 | 2.748 | 3.611 | 4.611 | 900 | 1.218 | 1.741 | 2.075 | 2.726 | 3.483 |
| 40 | 1.571 | 2.247 | 2.677 | 3.518 | 4.493 | 1000 | 1.214 | 1.736 | 2.068 | 2.718 | 3.472 |
| 45 | 1.539 | 2.200 | 2.621 | 3.444 | 4.399 | $\infty$ | 1.150 | 1.645 | 1.960 | 2.576 | 3.291 |
| 50 | 1.512 | 2.162 | 2.576 | 3.385 | 4.323 | | | | | | |

Table 7 - Location Coordinates and Maximum DAC for 18 Indications of Flaws in PVRC Specimen 251J As Reported by Team A (1968 UT Procedure).

## Team A (1968 Procedure) UT Data (Uncorrected)

***File Name:* [PVRC] UT68A.DAT**

| INDICA: | DACMAX. | X1UTA | X2UTA | Y1UTA | Y2UTA | Z1UTA | Z2UTA | UT68A.DAT |
|---|---|---|---|---|---|---|---|---|
| 1 | 50 | 25.79 | 25.81 | 32.10 | 33.10 | 7.99 | 8.01 | |
| 2 | 30 | 27.99 | 28.01 | 27.60 | 30.60 | 10.99 | 11.01 | |
| 3 | 50 | 27.59 | 27.61 | 27.60 | 30.60 | 12.99 | 13.01 | |
| 4 | 50 | 27.49 | 27.51 | 27.60 | 30.60 | 17.49 | 17.51 | |
| 5 | 30 | 28.59 | 28.61 | 12.30 | 17.30 | 5.49 | 5.51 | |
| 6 | 100 | 26.59 | 26.61 | 16.40 | 17.40 | 7.74 | 7.76 | |
| 7 | 50 | 27.99 | 28.01 | 13.40 | 17.40 | 14.99 | 15.01 | |
| 8 | 110 | 28.59 | 28.61 | 0.34 | 2.34 | 8.94 | 8.96 | |
| 9 | 50 | 27.19 | 27.21 | 1.35 | 2.59 | 16.99 | 17.01 | |
| 10 | 25 | 26.99 | 27.01 | 3.75 | 5.25 | 2.94 | 2.96 | |
| 11 | 40 | 27.99 | 28.01 | 0.44 | 1.94 | 4.99 | 5.01 | |
| 12 | 110 | 26.79 | 26.81 | 1.19 | 3.69 | 3.04 | 3.06 | |
| 13 | 80 | 26.99 | 27.01 | 2.25 | 3.75 | 9.04 | 9.06 | |
| 14 | 120 | 26.49 | 26.51 | 1.44 | 3.44 | 14.99 | 15.01 | |
| 15 | 100 | 27.79 | 27.81 | 13.20 | 16.00 | 19.99 | 20.01 | |
| 16 | 60 | 27.19 | 27.21 | 14.45 | 18.95 | 4.99 | 5.01 | |
| 17 | 50 | 26.49 | 26.51 | 16.70 | 17.70 | 14.74 | 14.76 | |
| 18 | 200 | 25.79 | 25.81 | 27.00 | 30.00 | 9.99 | 10.01 | |

$

Table 8 - Location Coordinates and Maximum DAC for 4 Indications of Flaws in PVRC Specimen 251J As Reported by Team B (1968 UT Procedure).

## Team B (1968 Procedure) UT Data (Uncorrected)

*File Name: [PVRC] UT68B.DAT*

| INDICA. | DACMAX. | X1UTB | X2UTB | Y1UTB | Y2UTB | Z1UTB | Z2UTB | UT68B.DAT |
|---|---|---|---|---|---|---|---|---|
| 1 | 25 | 25.20 | 25.70 | 2.00 | 6.00 | 5.50 | 6.60 | |
| 2 | 30 | 25.20 | 25.70 | 16.00 | 13.50 | 9.00 | 9.50 | |
| 3 | 25. | 26.30 | 26.70 | 16.30 | 22.30 | 6.50 | 7.00 | |
| 4 | 30 | 26.30 | 26.60 | 28.30 | 32.20 | 9.00 | 9.50 | |

$

Table 9 - Location Coordinates and Maximum DAC for 14 Indications of Flaws in PVRC Specimen 251J As Reported by Team C (1968 UT Procedure).

## Team C (1968 Procedure) UT Data (Uncorrected)

*File Name: [PVRC] UT68C.DAT*

| INDICA. | DACMAX. | X1UTC | X2UTC | Y1UTC | Y2UTC | Z1UTC | Z2UTC | UT68C.DAT |
|---|---|---|---|---|---|---|---|---|
| 1 | 100 | 24.98 | 25.02 | 15.50 | 18.50 | 0.98 | 1.02 | |
| 2 | 40 | 24.98 | 25.02 | 30.50 | 33.75 | 5.48 | 5.52 | |
| 3 | 75 | 24.98 | 25.02 | 1.00 | 4.50 | 9.98 | 10.02 | |
| 4 | 40 | 25.98 | 26.02 | 1.75 | 2.50 | 2.73 | 2.77 | |
| 5 | 60 | 25.98 | 26.02 | 16.00 | 21.00 | 8.23 | 8.27 | |
| 6 | 25 | 24.98 | 25.02 | 1.50 | 4.50 | 0.98 | 1.02 | |
| 7 | 40 | 26.48 | 26.52 | 30.00 | 34.25 | 2.73 | 2.77 | |
| 8 | 40 | 25.48 | 25.52 | 14.50 | 20.00 | 5.48 | 5.52 | |
| 9 | 45 | 25.98 | 26.02 | 1.00 | 6.00 | 8.23 | 8.27 | |
| 10 | 75 | 24.98 | 25.02 | 30.00 | 34.00 | 9.98 | 10.02 | |
| 11 | 11 | 25.98 | 26.02 | 31.98 | 32.02 | 0.98 | 1.02 | |
| 12 | 9 | 25.98 | 26.02 | 16.98 | 17.02 | 2.73 | 2.77 | |
| 13 | 8 | 25.98 | 26.02 | 1.98 | 2.02 | 5.48 | 5.52 | |
| 14 | 9 | 25.98 | 26.02 | 16.98 | 17.02 | 9.98 | 10.02 | |

$

Table 10 - Location Coordinates and Maximum DAC for 6 Indications of Flaws in PVRC Specimen 251J As Reported by Team D (1968 UT Procedure).

## Team D (1968 Procedure) UT Data (Uncorrected)

*File Name: [PVRC] UT68D.DAT*

| INDICA. | DACMAX. | X1UTD | X2UTD | Y1UTD | Y2UTD | Z1UTD | Z2UTD | UT68D.DAT |
|---|---|---|---|---|---|---|---|---|
| 1 | 100 | 30.48 | 30.52 | 3.00 | 4.50 | 2.98 | 3.02 | |
| 2 | 100 | 33.92 | 33.96 | 17.00 | 20.00 | 5.48 | 5.52 | |
| 3 | 100 | 36.23 | 36.27 | 30.00 | 31.00 | 7.00 | 10.00 | |
| 4 | 70 | 14.11 | 14.15 | 30.50 | 34.00 | 8.00 | 11.00 | |
| 5 | 100 | 17.98 | 18.02 | 17.00 | 18.00 | 5.00 | 11.00 | |
| 6 | 100 | 12.38 | 12.42 | 1.75 | 3.50 | 8.98 | 9.02 | |

$

Table 11 - Location Coordinates and Maximum DAC for 31 Indications of Flaws in PVRC Specimen 251J As Reported by Team F (1968 UT Procedure).

## Team F (1968 Procedure) UT Data (Uncorrected)

***File Name: [PVRC] UT68F.DAT***

| INDICA. | DACMAX. | X1UTF | X2UTF | Y1UTF | Y2UTF | Z1UTF | Z2UTF | UT68F.DAT |
|---|---|---|---|---|---|---|---|---|
| 1 | 41 | 25.50 | 25.75 | 32.50 | 31.87 | 7.50 | 8.37 | |
| 2 | 100 | 25.50 | 27.00 | 30.00 | 32.00 | 0.02 | 0.87 | |
| 3 | 60 | 24.48 | 24.52 | 31.35 | 31.39 | 1.48 | 1.52 | |
| 4 | 55 | 25.48 | 25.52 | 30.60 | 30.64 | 7.48 | 7.52 | |
| 5 | 62 | 24.35 | 24.39 | 30.73 | 30.77 | 0.02 | 0.04 | |
| 6 | 107 | 25.48 | 25.52 | 29.98 | 30.02 | 0.35 | 0.39 | |
| 7 | 38 | 25.98 | 26.02 | 29.23 | 29.27 | 10.35 | 10.39 | |
| 8 | 86 | 25.23 | 25.27 | 26.50 | 26.37 | 0.02 | 0.04 | |
| 9 | 71 | 25.48 | 25.52 | 21.85 | 21.89 | 0.02 | 0.04 | |
| 10 | 70 | 25.25 | 25.50 | 17.75 | 18.25 | 5.12 | 6.00 | |
| 11 | 38 | 26.73 | 26.77 | 17.23 | 17.27 | 10.35 | 10.39 | |
| 12 | 68 | 24.98 | 25.02 | 16.73 | 16.77 | 8.35 | 8.39 | |
| 13 | 38 | 25.50 | 25.75 | 16.25 | 16.75 | 5.12 | 6.12 | |
| 14 | 150 | 25.73 | 25.77 | 15.37 | 16.37 | 0.02 | 0.87 | |
| 15 | 57 | 26.48 | 26.52 | 10.98 | 11.02 | 0.02 | 0.04 | |
| 16 | 70 | 25.98 | 26.02 | 4.35 | 4.39 | 4.48 | 4.52 | |
| 17 | 200 | 26.48 | 26.52 | 2.48 | 2.52 | 5.35 | 5.39 | |
| 18 | 200 | 25.48 | 25.52 | 2.48 | 2.52 | 3.23 | 3.27 | |
| 19 | 93 | 25.75 | 27.25 | 1.75 | 3.00 | 9.25 | 10.75 | |
| 20 | 90 | 25.73 | 25.77 | 5.73 | 5.77 | 2.48 | 2.52 | |
| 21 | 57 | 25.48 | 25.52 | 5.73 | 5.77 | 0.02 | 0.04 | |
| 22 | 110 | 26.50 | 27.00 | 4.00 | 5.00 | 5.12 | 5.37 | |
| 23 | 150 | 25.50 | 26.00 | 4.50 | 6.00 | 2.75 | 3.50 | |
| 24 | 46 | 24.98 | 25.02 | 2.35 | 2.39 | 2.60 | 2.64 | |
| 25 | 57 | 27.48 | 27.52 | 13.48 | 13.52 | 0.10 | 0.14 | |
| 26 | 43 | 26.98 | 27.02 | 15.48 | 15.52 | 0.02 | 0.04 | |
| 27 | 200 | 26.75 | 27.50 | 17.00 | 18.50 | 0.02 | 2.37 | |
| 28 | 200 | 26.00 | 26.50 | 19.00 | 19.75 | 5.98 | 6.02 | |
| 29 | 43 | 24.98 | 25.02 | 28.23 | 28.27 | 0.02 | 0.04 | |
| 30 | 159 | 26.50 | 27.00 | 30.00 | 31.37 | 9.37 | 10.75 | |
| 31 | 73 | 26.23 | 26.27 | 23.73 | 23.77 | 6.23 | 6.27 | |

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Table 12 - Team A (1968 Procedure) UT Data As Corrected by Hedden for PVRC Subcommittee on NDE of Pressure Components (Feb. 17, 1984).

## Team A (1968 Proced.) UT Data (Hedden, 84-02-17)

***File Name:* [PVRC] *UT68AX.DAT***

| INDICA. | DACMAX. | X1UAX | X2UAX | Y1UAX | Y2UAX | Z1UAX | Z2UAX | UT68AX. |
|---|---|---|---|---|---|---|---|---|
| 1 | 50 | 24.79 | 24.81 | 32.10 | 33.10 | 7.99 | 8.01 | |
| 2 | 80 | 26.99 | 27.01 | 27.60 | 30.60 | 10.99 | 11.01 | |
| 3 | 50 | 26.59 | 26.61 | 27.60 | 30.60 | 8.99 | 9.01 | |
| 4 | 50 | 26.49 | 26.51 | 27.60 | 30.60 | 4.49 | 4.51 | |
| 5 | 80 | 27.59 | 27.61 | 12.30 | 17.30 | 5.49 | 5.51 | |
| 6 | 100 | 25.59 | 25.61 | 16.40 | 17.40 | 7.74 | 7.76 | |
| 7 | 50 | 26.99 | 27.01 | 13.40 | 17.40 | 6.99 | 7.01 | |
| 8 | 110 | 27.59 | 27.61 | 0.34 | 2.34 | 8.94 | 8.96 | |
| 9 | 50 | 26.19 | 26.21 | 1.35 | 2.59 | 5.04 | 5.06 | |
| 10 | 25 | 25.99 | 26.01 | 3.75 | 5.25 | 2.94 | 2.96 | |
| 11 | 40 | 26.99 | 27.01 | 0.44 | 1.94 | 4.94 | 4.96 | |
| 12 | 110 | 25.79 | 25.81 | 1.19 | 3.69 | 3.04 | 3.06 | |
| 13 | 80 | 25.99 | 26.01 | 2.25 | 3.75 | 9.04 | 9.06 | |
| 14 | 120 | 25.49 | 25.51 | 1.44 | 3.44 | 6.99 | 7.01 | |
| 15 | 100 | 26.79 | 26.81 | 13.20 | 16.00 | 1.99 | 2.01 | |
| 16 | 60 | 26.19 | 26.21 | 14.45 | 18.95 | 4.99 | 5.01 | |
| 17 | 50 | 25.49 | 25.51 | 16.70 | 17.70 | 7.19 | 7.21 | |
| 18 | 200 | 24.79 | 24.81 | 27.00 | 30.00 | 9.99 | 10.01 | |

$

Table 13 - Team A (1968 Procedure) UT Data As Corrected by Hedden for PVRC Subcommittee on NDE of Pressure Components (March 7, 1984).

## Team A (1968 Proced.) UT Data (Hedden, 84-03-07)

*File Name: [PVRC] UT68AY.DAT*

| INDICA. | DACMAX. | X1UAY | X2UAY | Y1UAY | Y2UAY | Z1UAY | Z2UAY | UT68AY. |
|---|---|---|---|---|---|---|---|---|
| 1 | 50 | 24.79 | 24.81 | 30.60 | 32.60 | 7.99 | 8.01 | |
| 2 | 80 | 25.59 | 25.61 | 28.95 | 31.95 | 9.35 | 10.45 | |
| 3 | 50 | 24.59 | 24.61 | 29.05 | 32.05 | 10.30 | 10.65 | |
| 4 | 50 | 26.49 | 26.51 | 29.00 | 32.00 | 4.49 | 4.51 | |
| 5 | 80 | 25.89 | 25.91 | 14.80 | 19.80 | 4.65 | 5.75 | |
| 6 | 100 | 25.79 | 25.81 | 16.80 | 17.80 | 8.29 | 8.31 | |
| 7 | 50 | 25.79 | 25.81 | 15.30 | 19.30 | 7.84 | 7.86 | |
| 8 | 110 | 26.59 | 26.61 | 1.50 | 4.00 | 8.14 | 8.15 | |
| 9 | 50 | 24.79 | 24.81 | 1.80 | 3.00 | 6.24 | 6.26 | |
| 10 | 25 | 25.59 | 25.61 | 4.30 | 5.80 | 3.00 | 3.69 | |
| 11 | 40 | 25.59 | 25.61 | 2.30 | 4.80 | 3.40 | 3.95 | |
| 12 | 110 | 25.59 | 25.61 | 1.80 | 3.30 | 3.00 | 4.05 | |
| 13 | 80 | 26.59 | 26.61 | 3.00 | 4.50 | 8.24 | 8.26 | |
| 14 | 120 | 24.79 | 24.81 | 2.30 | 4.30 | 6.34 | 6.36 | |
| 15 | 100 | 26.79 | 26.31 | 15.00 | 18.00 | 1.99 | 2.01 | |
| 16 | 60 | 25.89 | 25.91 | 16.20 | 20.50 | 4.75 | 5.85 | |
| 17 | 50 | 25.79 | 25.81 | 17.50 | 19.00 | 7.74 | 7.76 | |
| 18 | 200 | 24.60 | 25.60 | 28.50 | 31.50 | 9.45 | 10.55 | |

$

LIST OF FIGURES

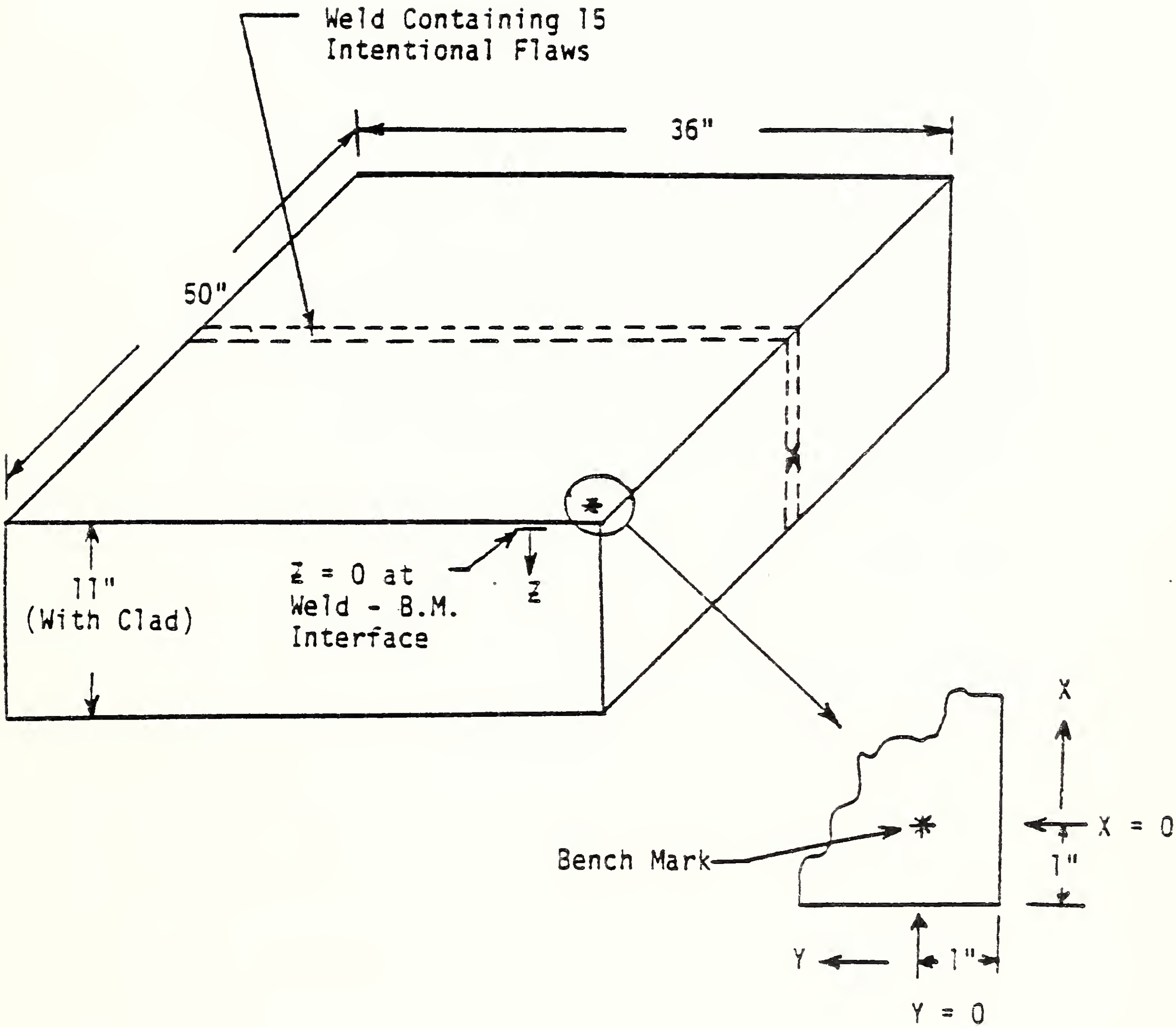



Fig. 1 Dimensions of PVRC Specimen 251J. After Yukawa (1983).

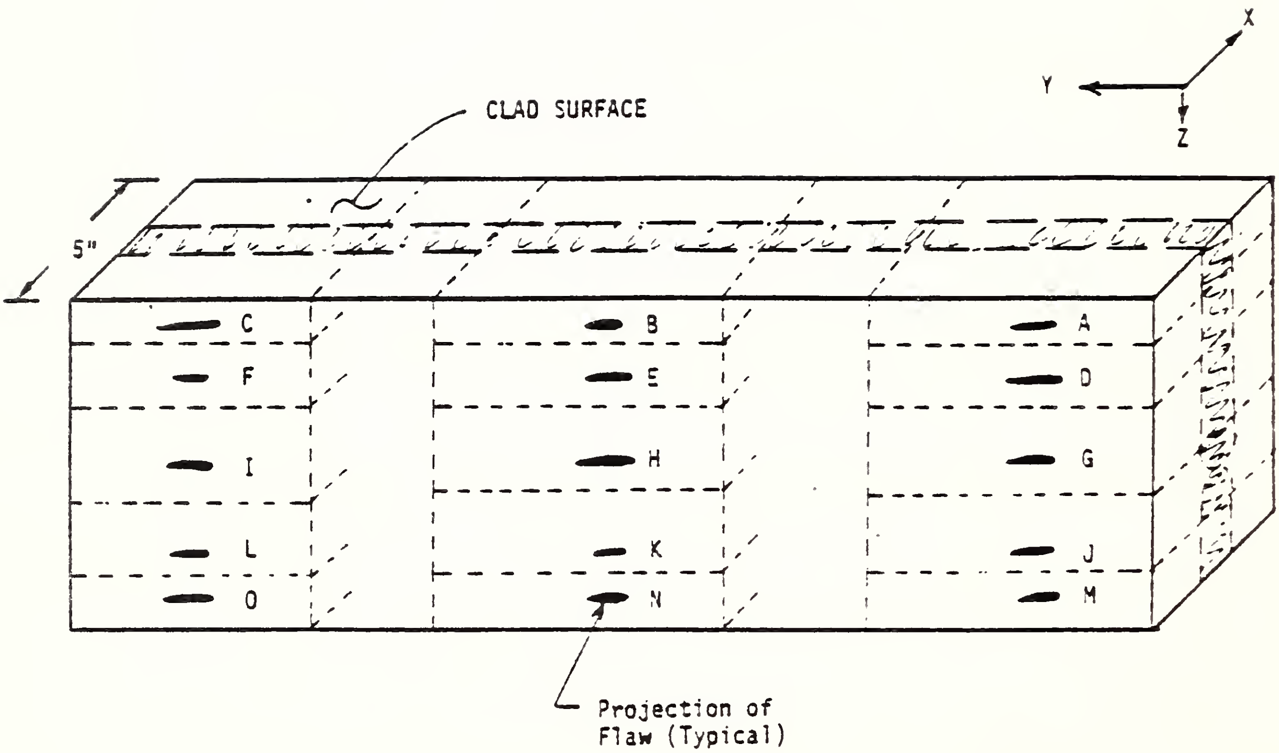



Fig. 2 Principal Sectioning Cuts. After Yukawa (1983).

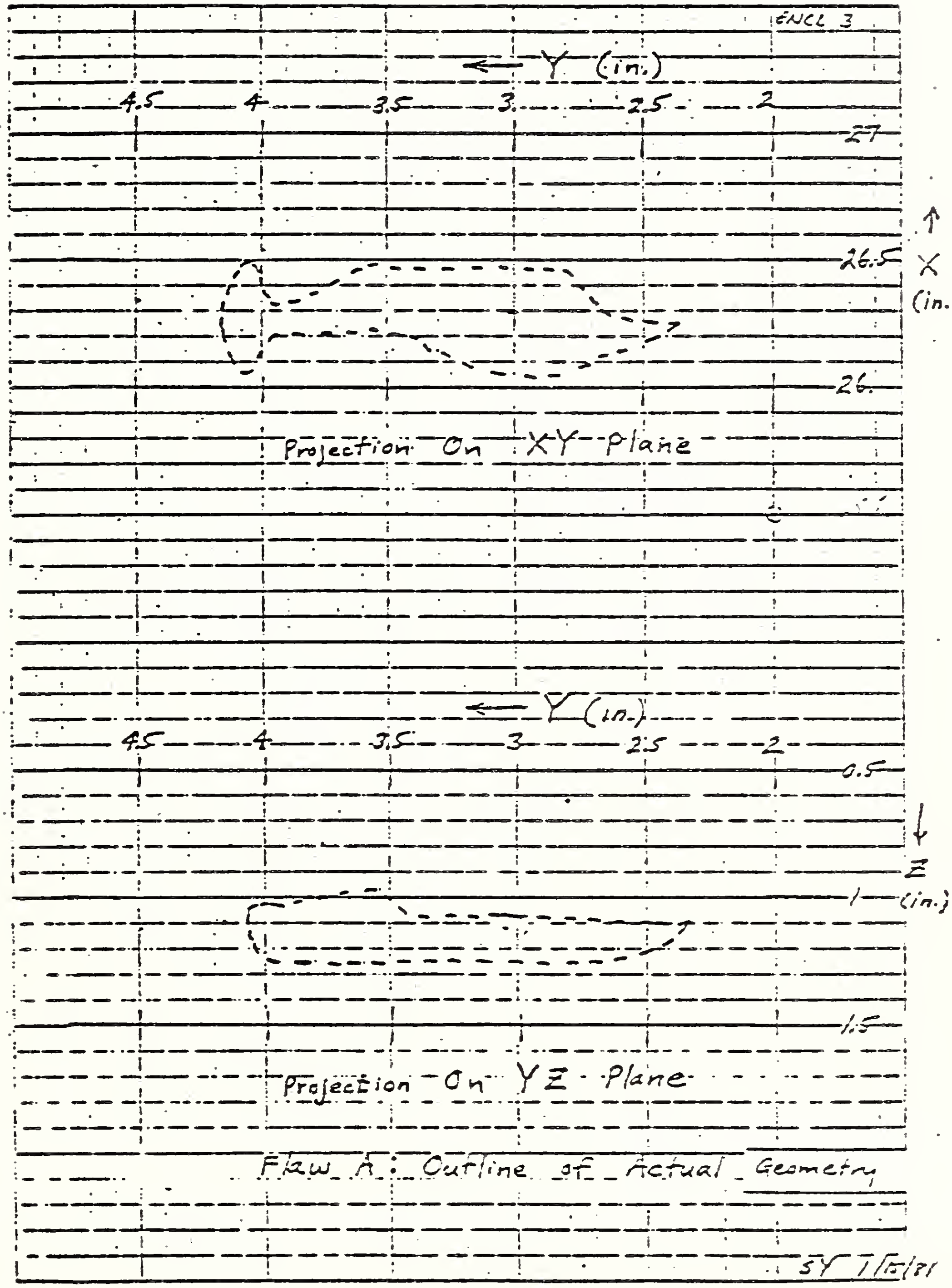



Fig. 3 Outline of Flaw A as Projected on the XY and YZ Planes. After Yukawa (1981).

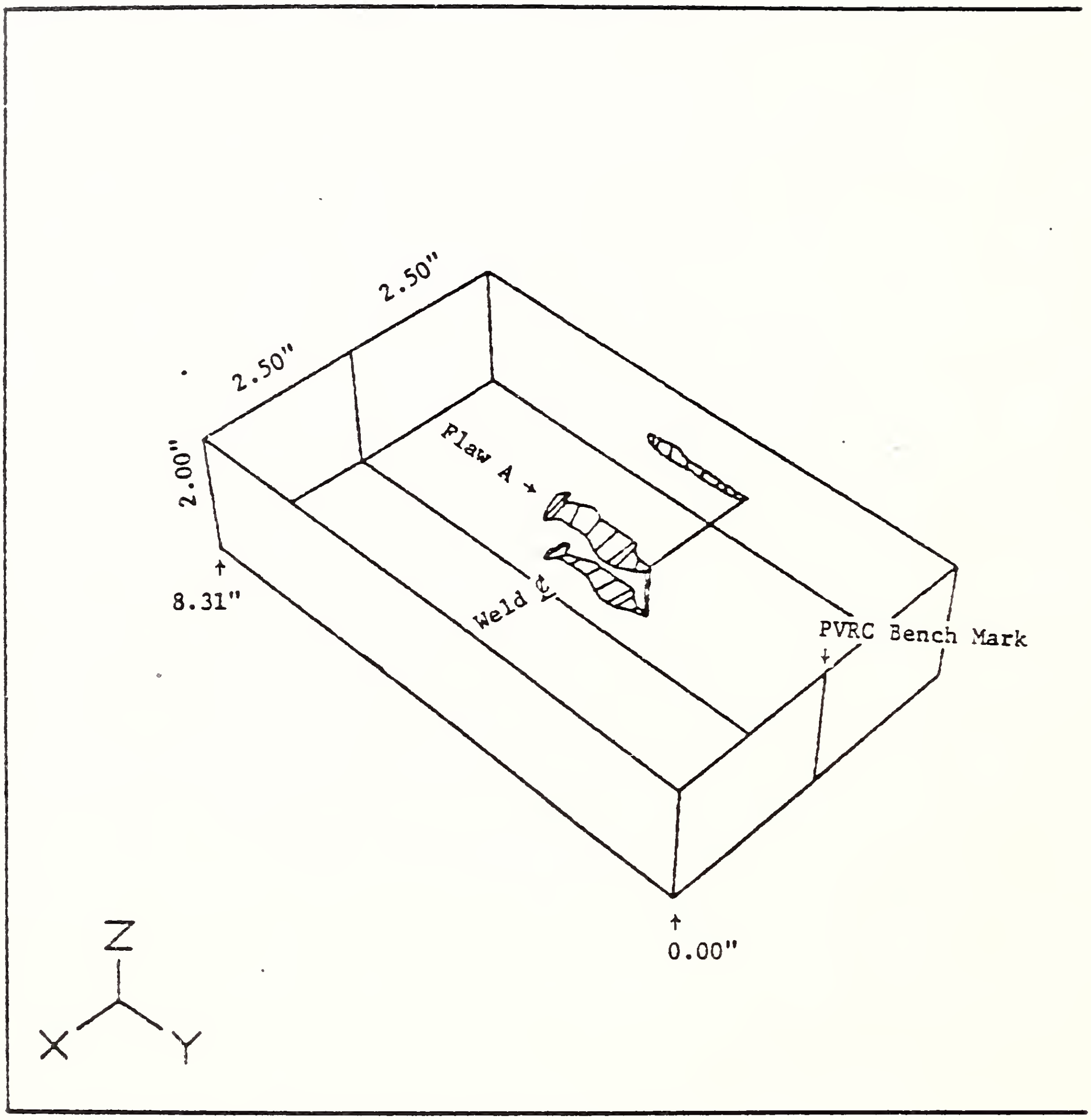



Fig. 4 A 3-Dimensional Computer-Aided Graphical Representation of Flaw A Based on its Projected Outline (Yukawa, 1981).

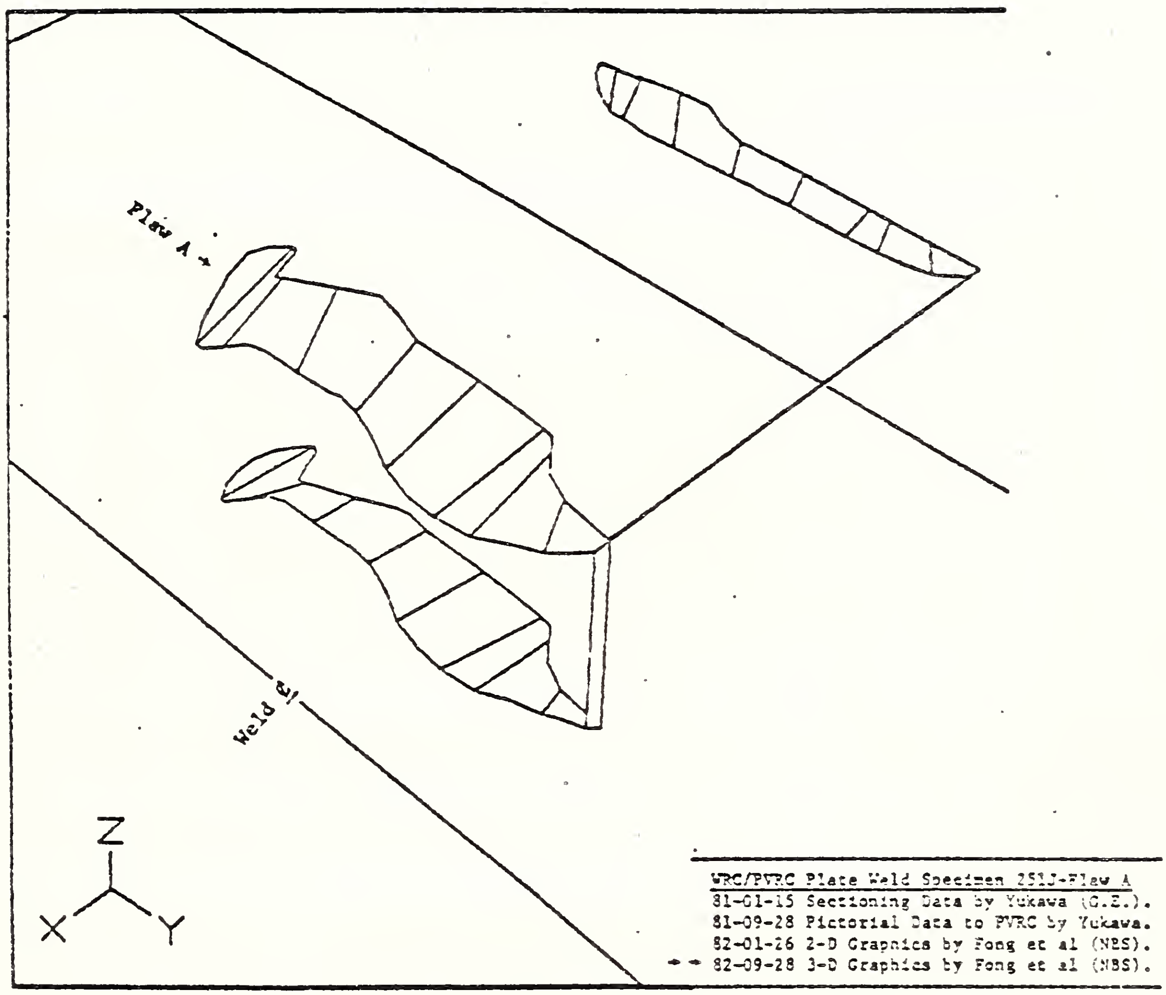



Fig. 5 An Enlarged View of Flaw A As Reconstructed from XY and YZ projections with the assumption that any XZ section of the flaw is a straight line.

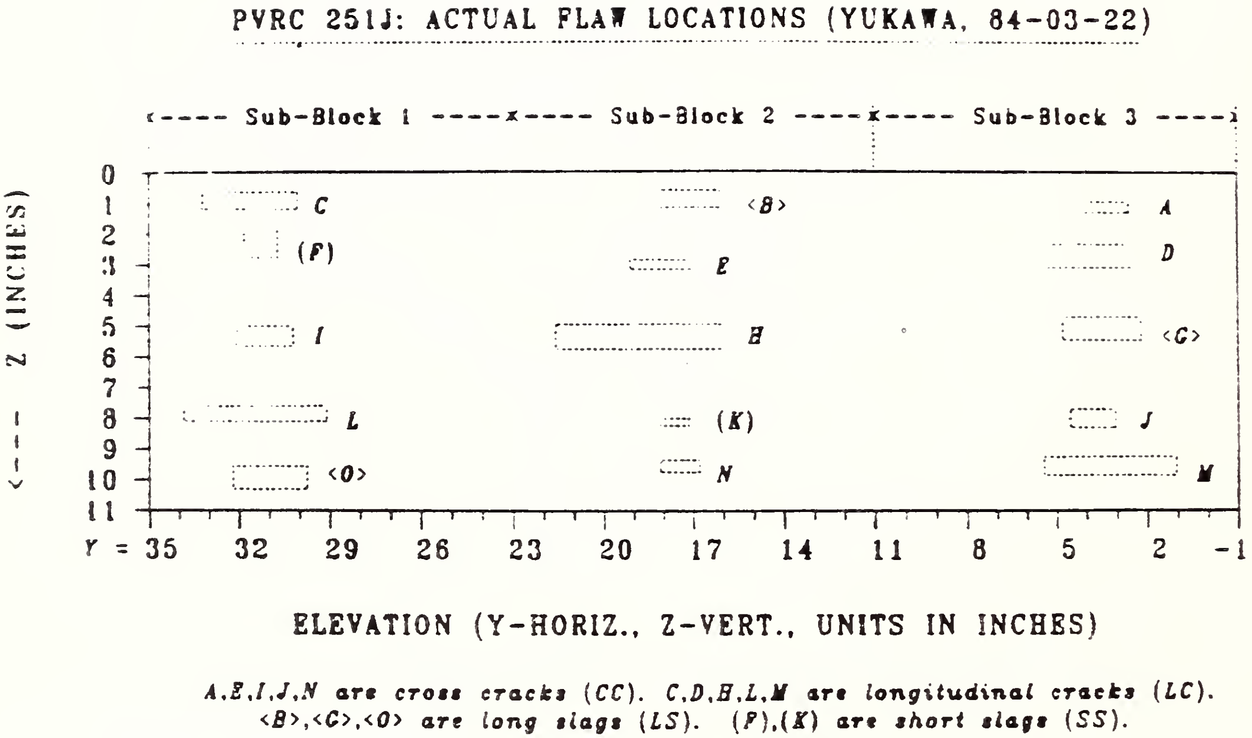
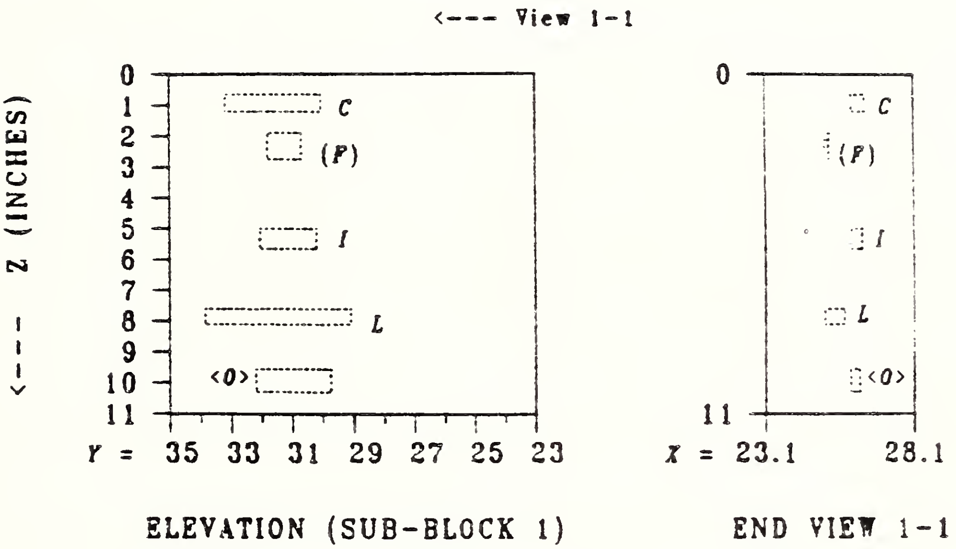



Fig. 6 Elevation of PVRC 251J showing the actual locations of 15 flaws as characterized in Table 3. After Yukawa (1984).

## ACTUAL FLAW LOCATIONS (YUKAWA, 84-03-22): SUB-BLOCK 1




*C & L are longitudinal cracks. I is a cross crack. (F): short slag. <O>: long slag. Scale in inches.*

Fig. 7 Elevation and End View of Sub-Block 1 to show actual locations of 5 flaws (Yukawa, 1984).

[PVRC] SECT8403Y.DP2

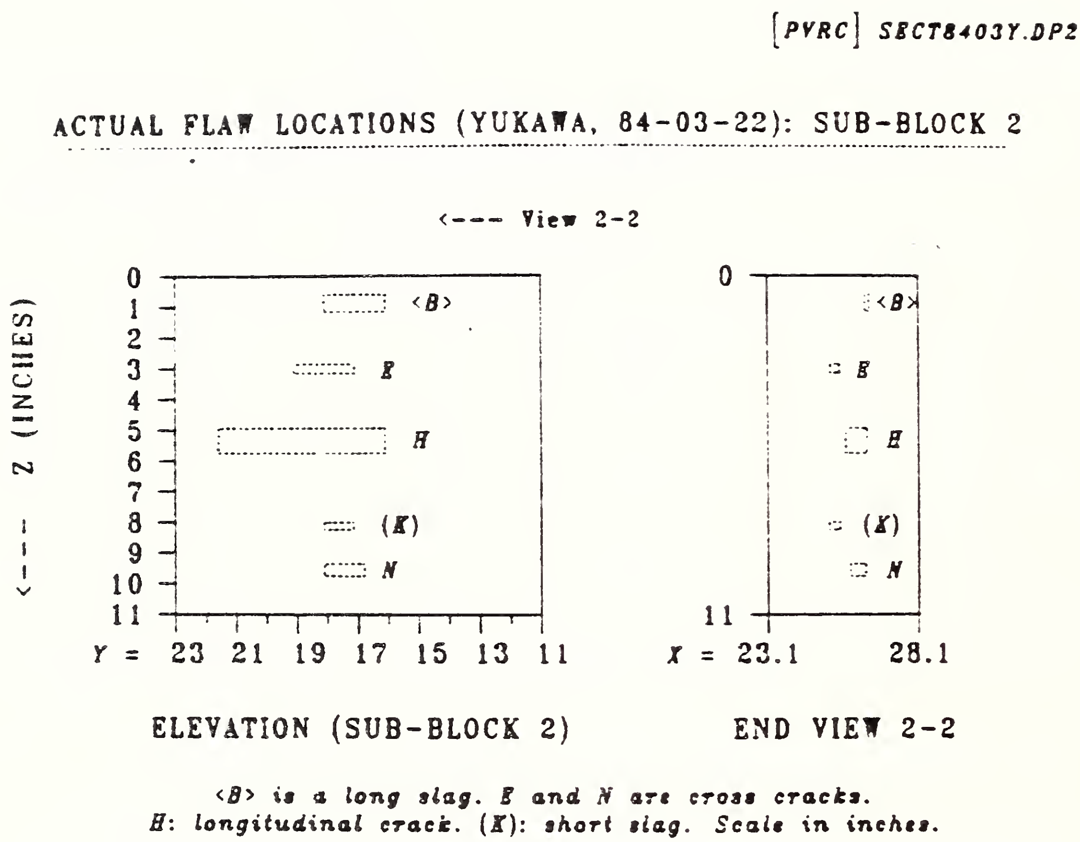



Fig. 8 Elevation and End View of Sub-Block 2 to show actual locations of 5 flaws (Yukawa, 1984).

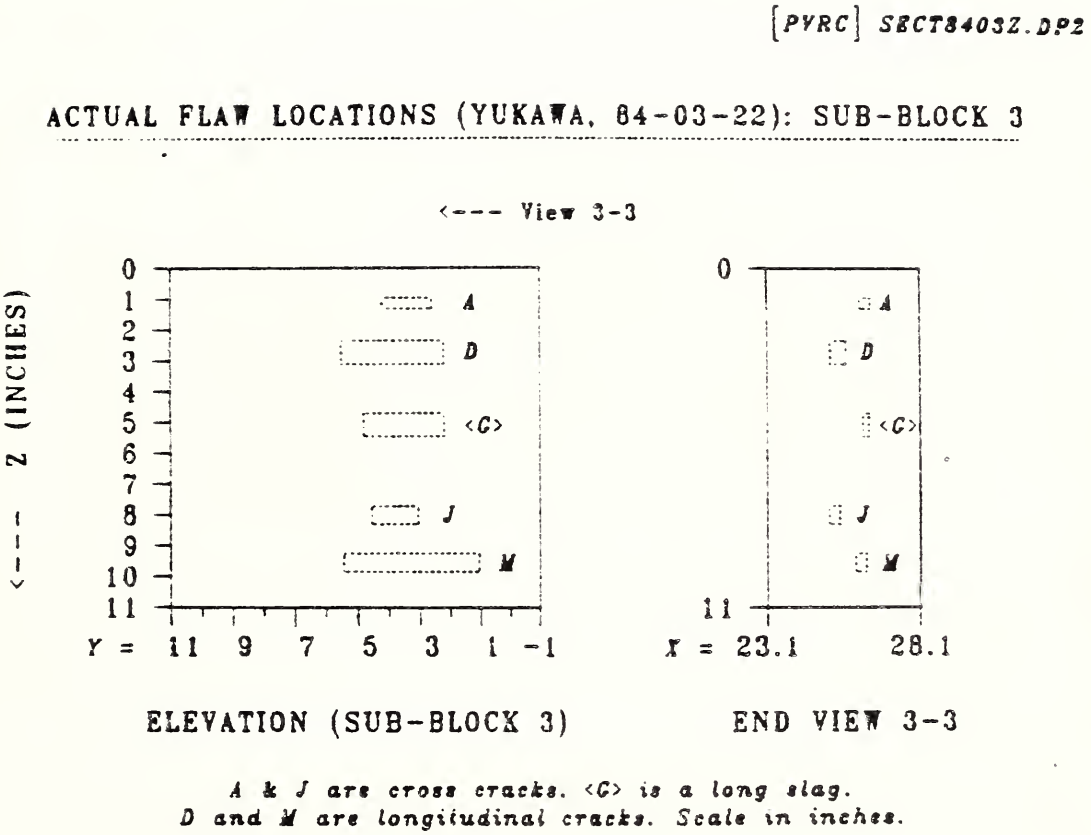



Fig. 9 Elevation and End View of Sub-Block 3 to show actual locations of 5 flaws (Yukawa, 1984).

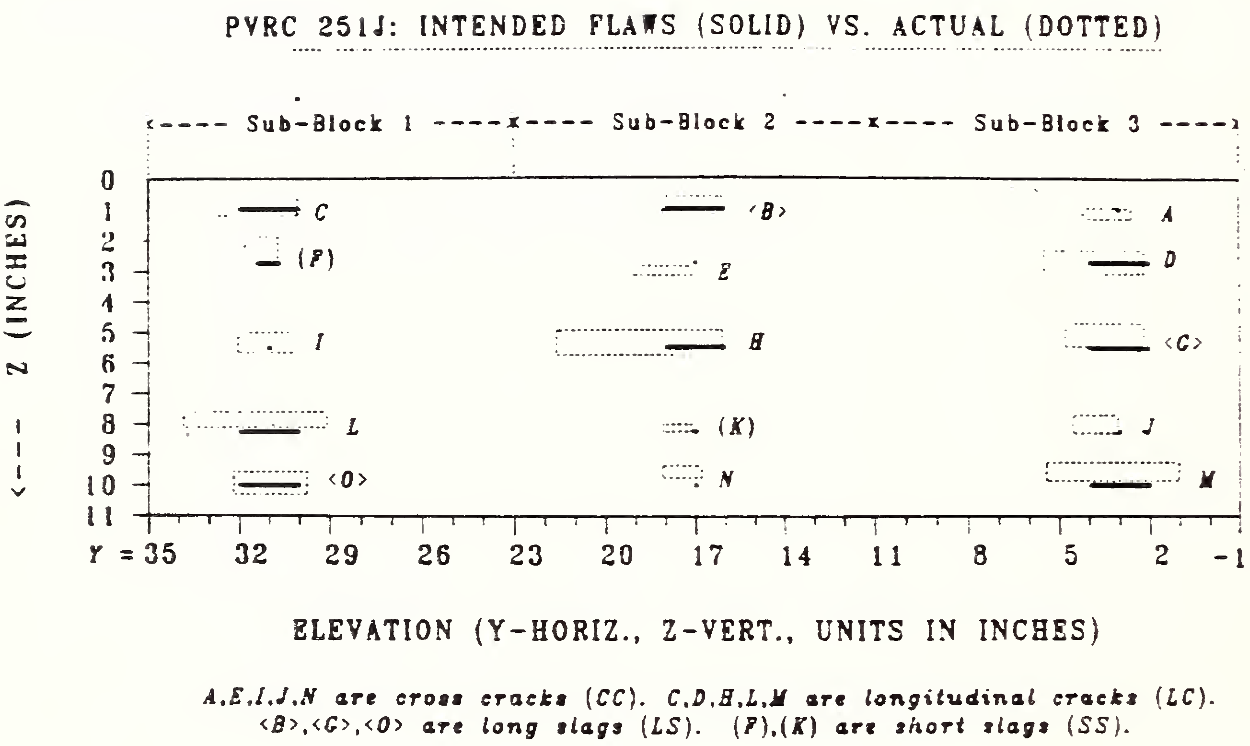



Fig. 10 Comparison of Intended (Solid Line) vs. Actual (Dotted Line) Locations of 15 Flaws as shown in the Elevation of the Entire Block 251J.

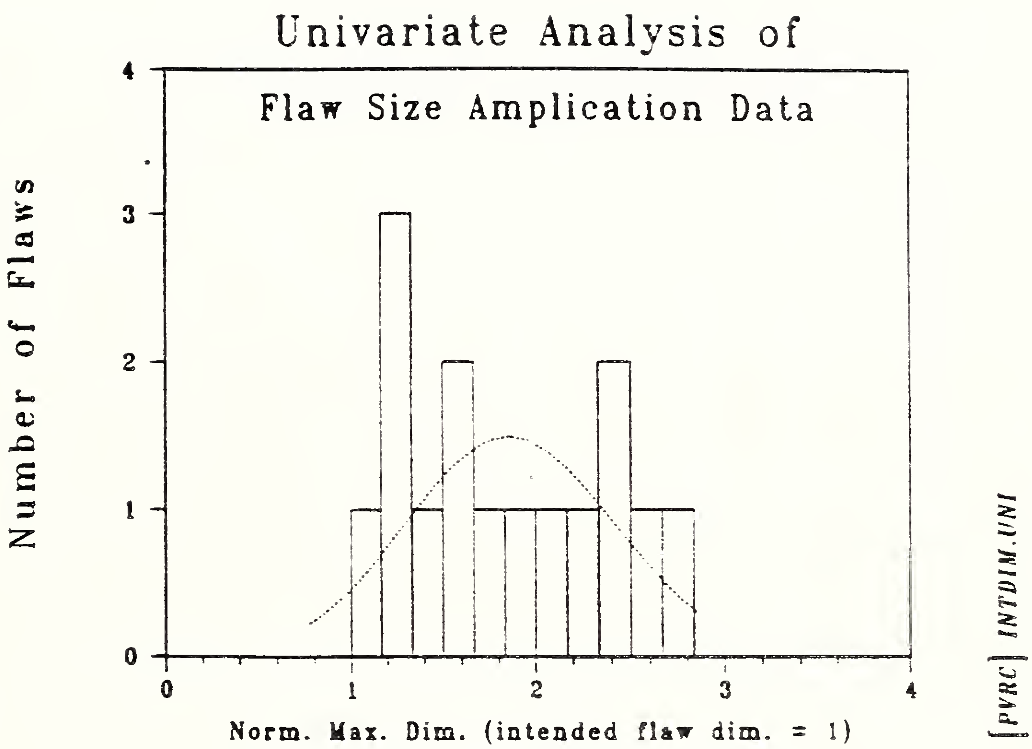



Fig. 11 Histogram and Normal Distribution Plot for Normalized Maximum Flaw Dimension Data (Intended Maximum Dimension equals unity).

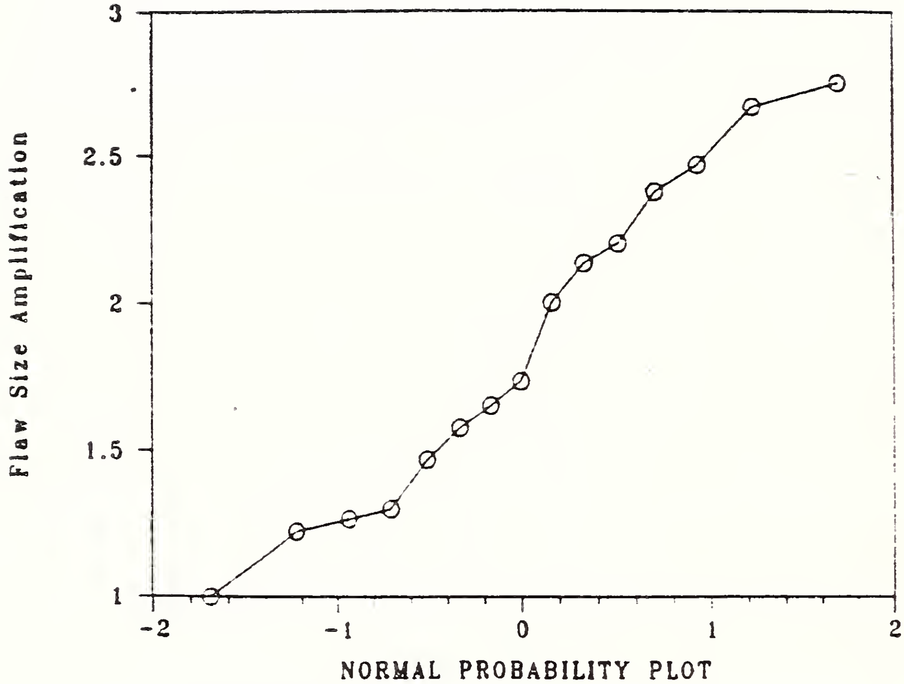



Fig. 12 Probability Plot for Testing a Normal Distribution Fit for Flaw Size Amplification Data

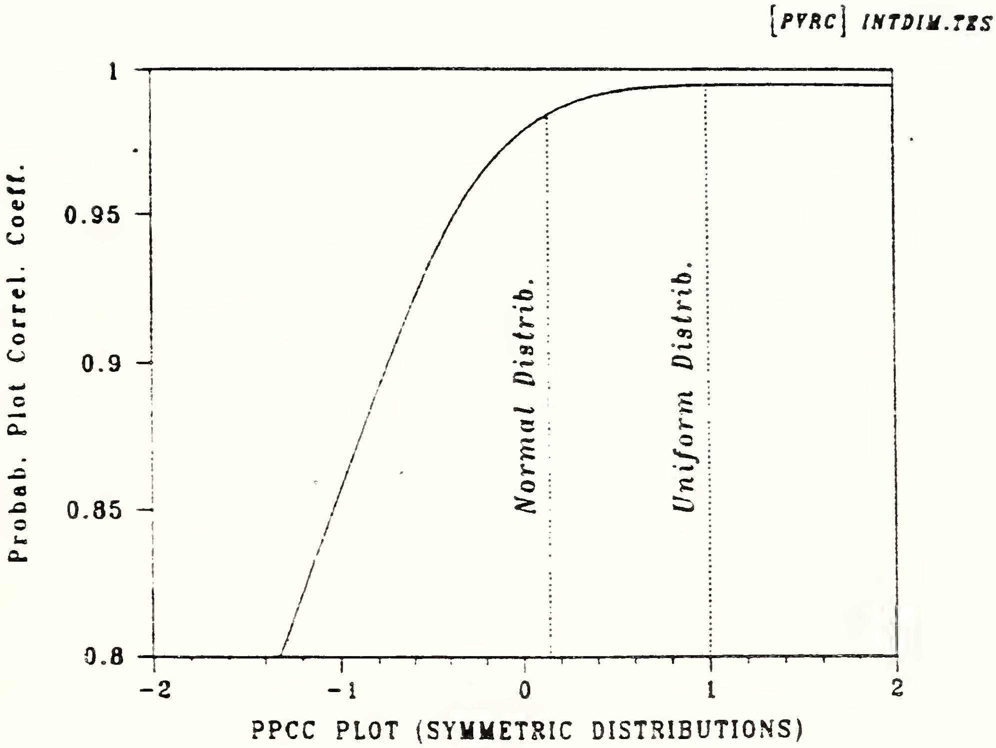



Fig. 13 Lambda Test for Symmetric Distribution Fit of Flaw Size Amplification Data. After Filliben (1969) and Joiner-Rosenblatt (1971).

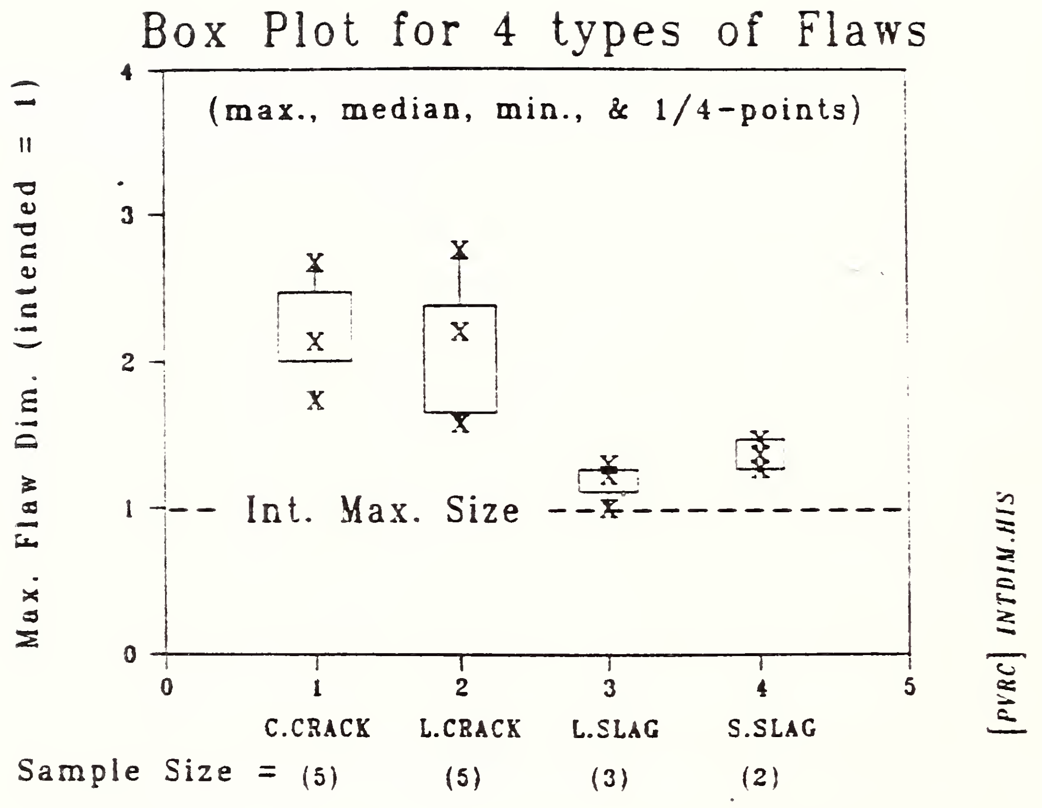



Fig. 14 Box Plot for 4 Different Types of Flaws to check suitability of introducing Analysis of Variance (ANOVA) for estimating between-type variability.

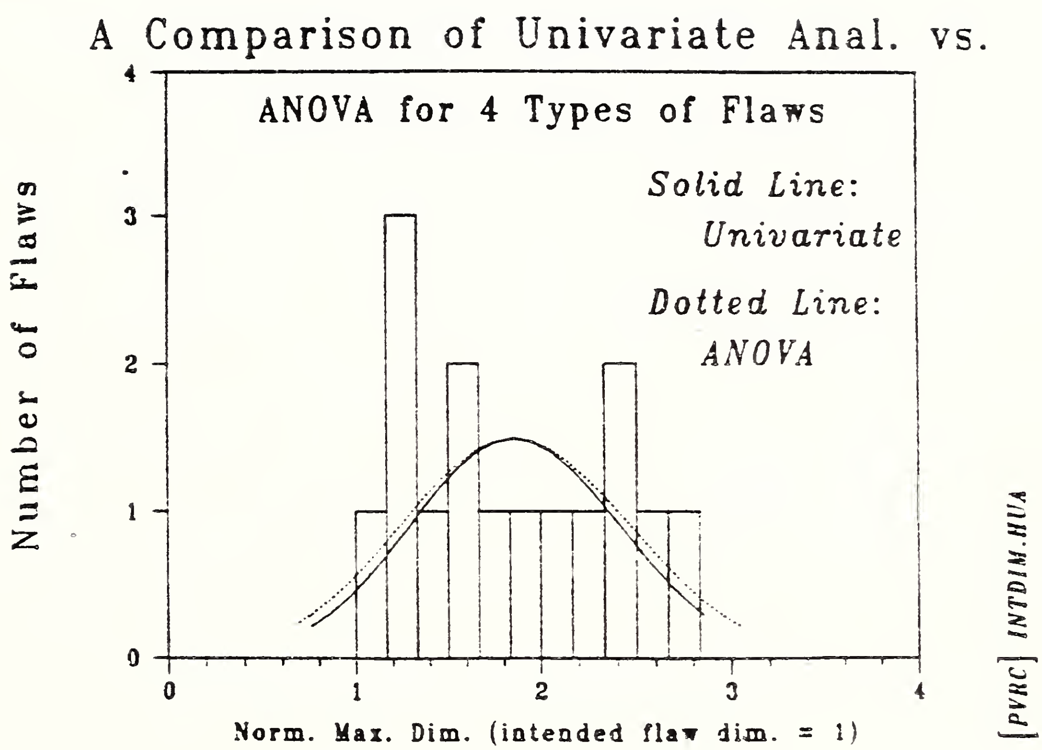



Fig. 15 Normal Distribution Plots for Normalized Maximum Dimension Data with or without estimating the between-type variability.

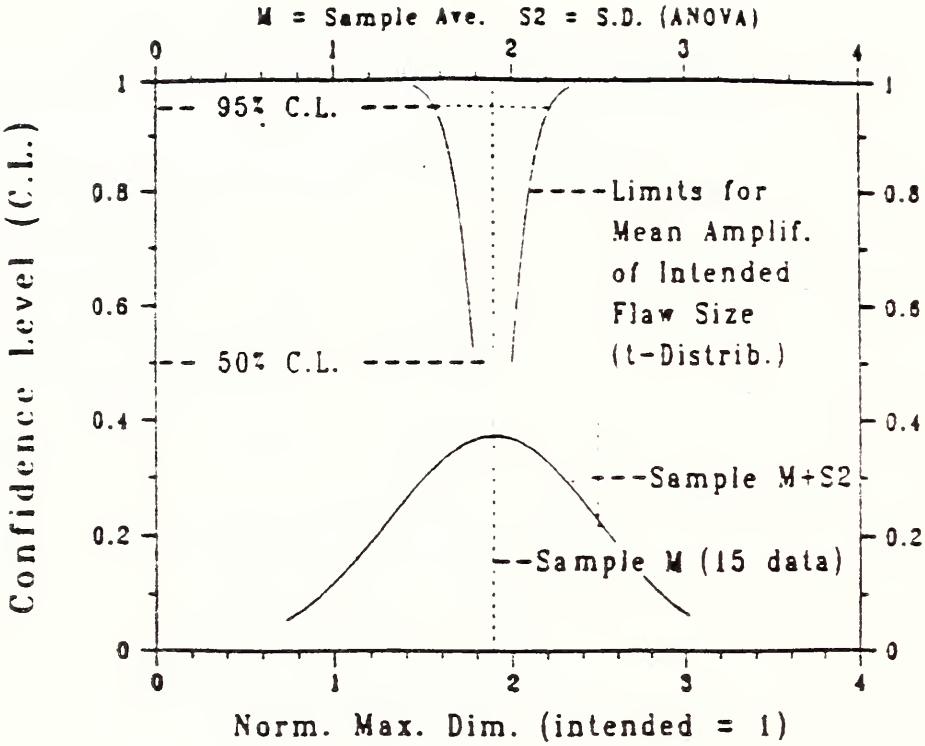



Fig. 16 Upper and Lower Limits for Mean Amplification of Intended Flaw Size for Confidence Levels between 50% and 95%.

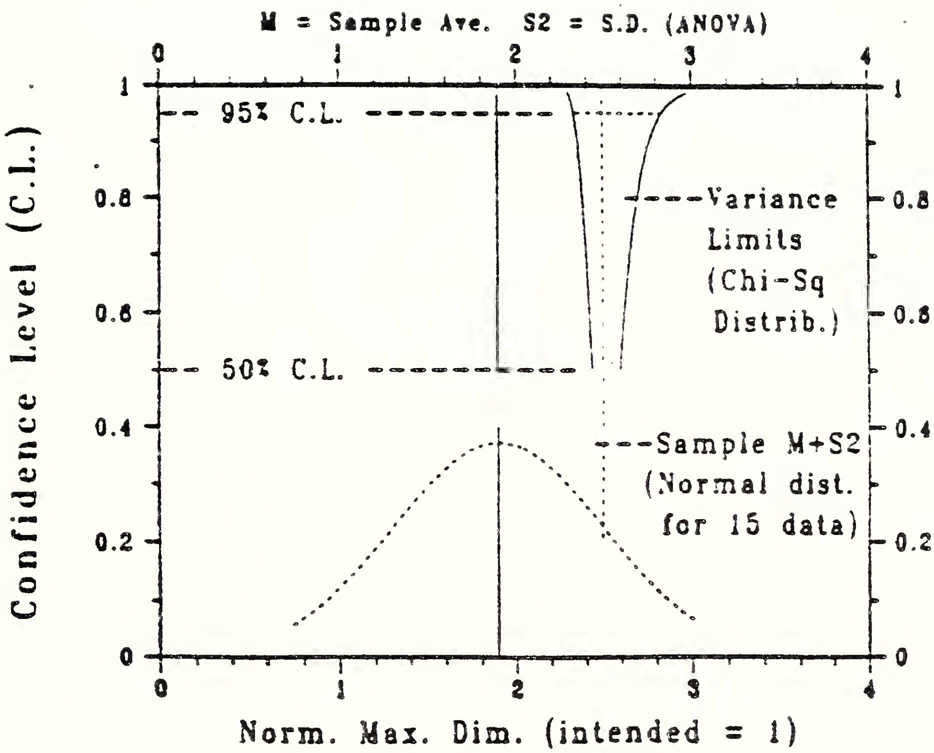



Fig. 17 Upper and Lower Limits for Variance of the Flaw Size Data for Confidence Levels between 50% and 95%.

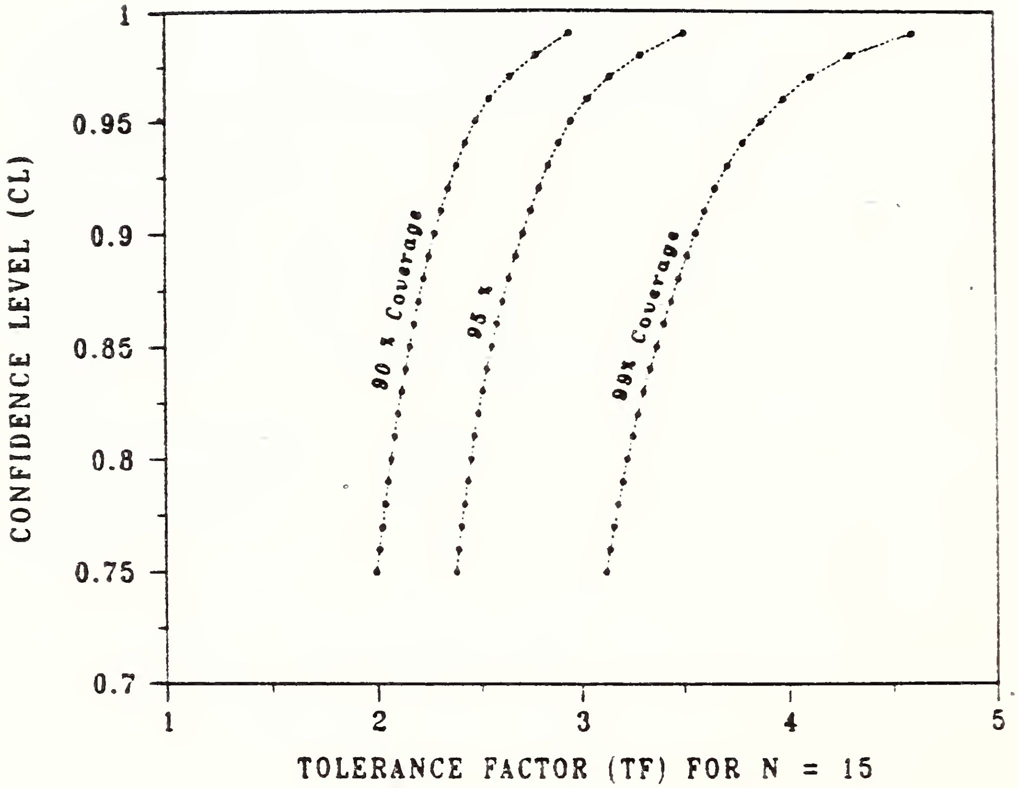



Fig. 18 Tolerance Factors (TF or K) for Sample Size N=15 and 3 population coverages (90%. 95%, & 99%), as interpolated from Tables 4,5, & 6 (Beyer, 1966).

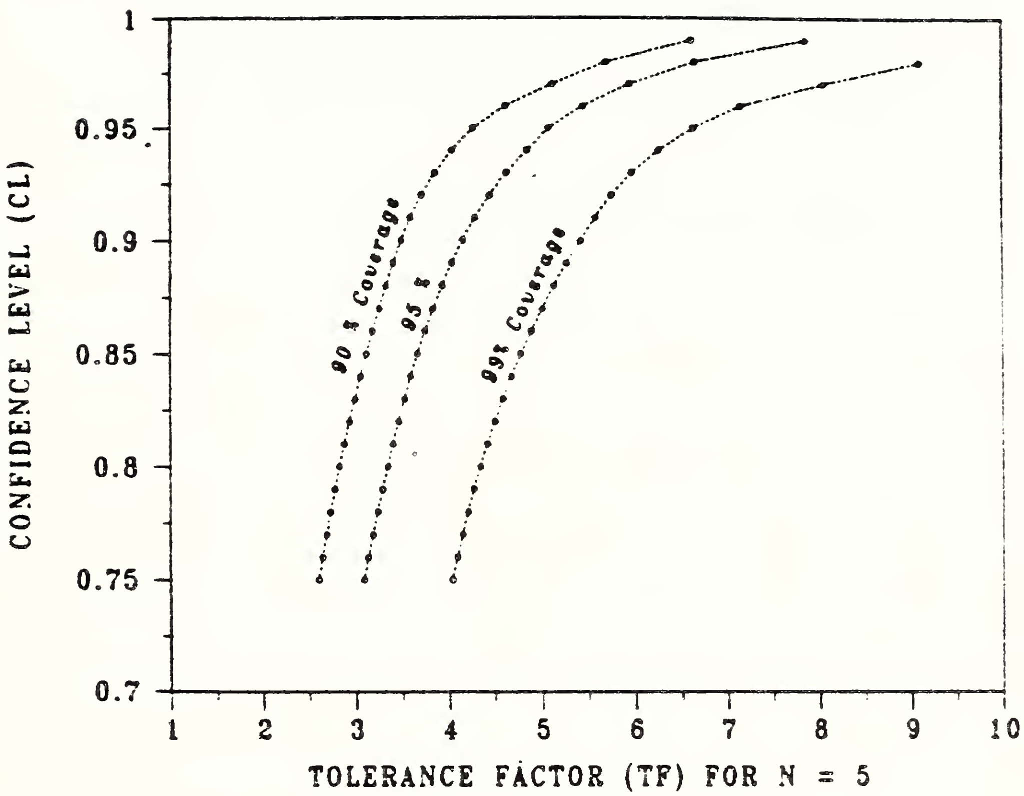



Fig. 19 Tolerance Factors (TF or K) for Sample Size N= 5 and 3 population coverages (90%. 95%, & 99%), as interpolated from Tables 4,5, & 6 (Beyer, 1966).

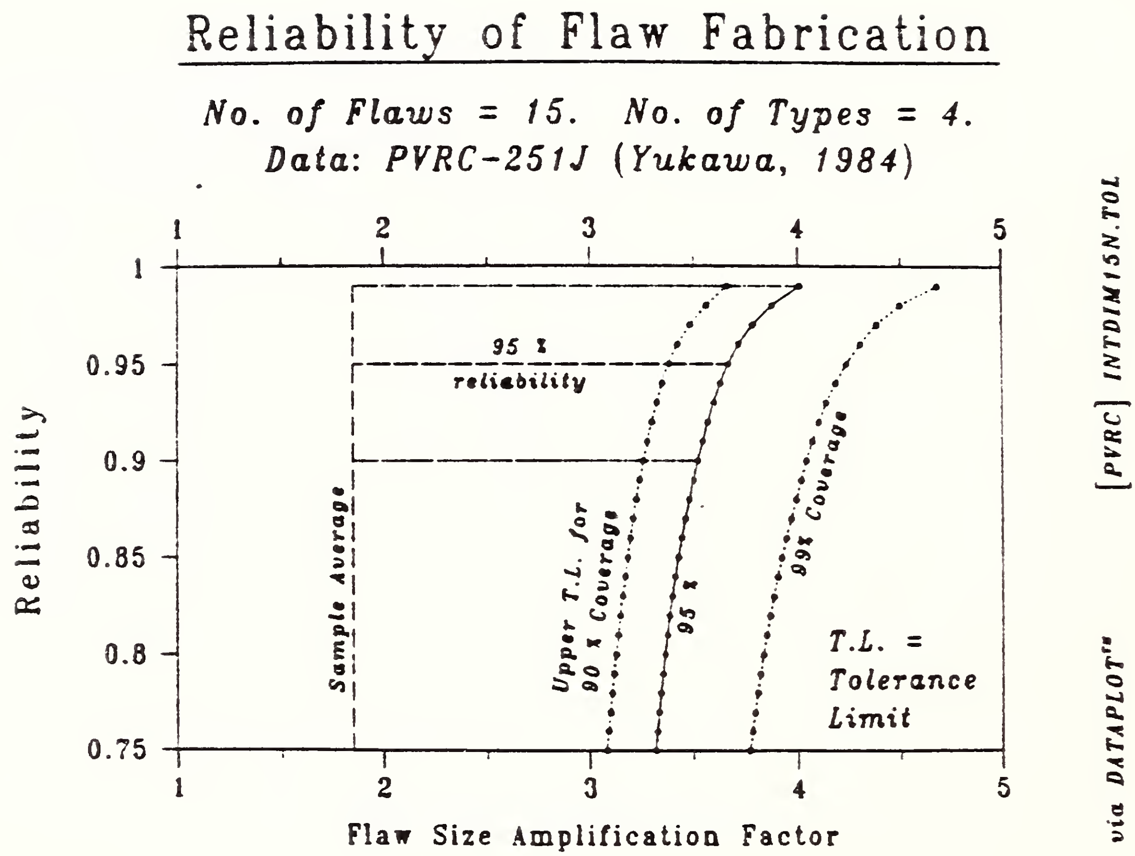



Fig. 20 Reliability of Flaw Fabrication As Defined by the Upper Tolerance Limit Curves for 3 coverages with the inclusion of between-type variability.

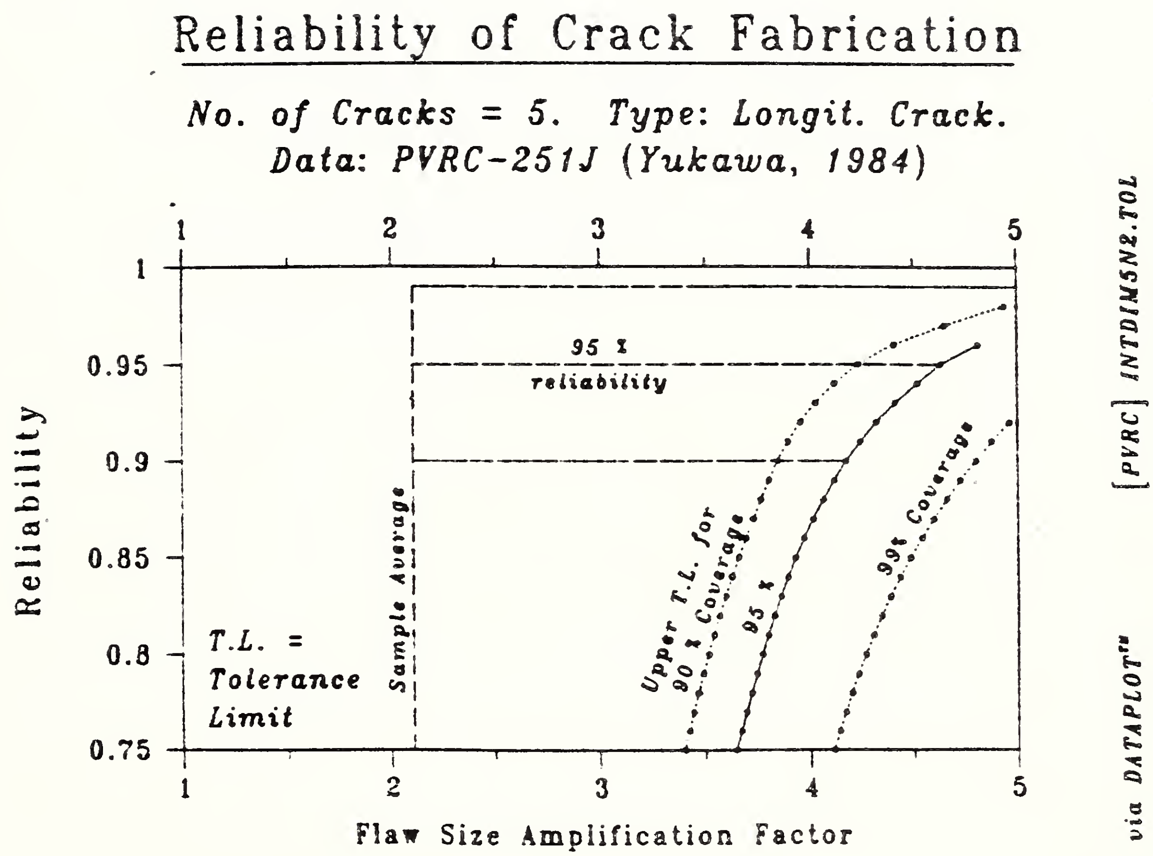



Fig. 21 Reliability of Longitudinal Crack Fabrication as Defined by the Upper Tolerance Limit Curves for 3 coverages.

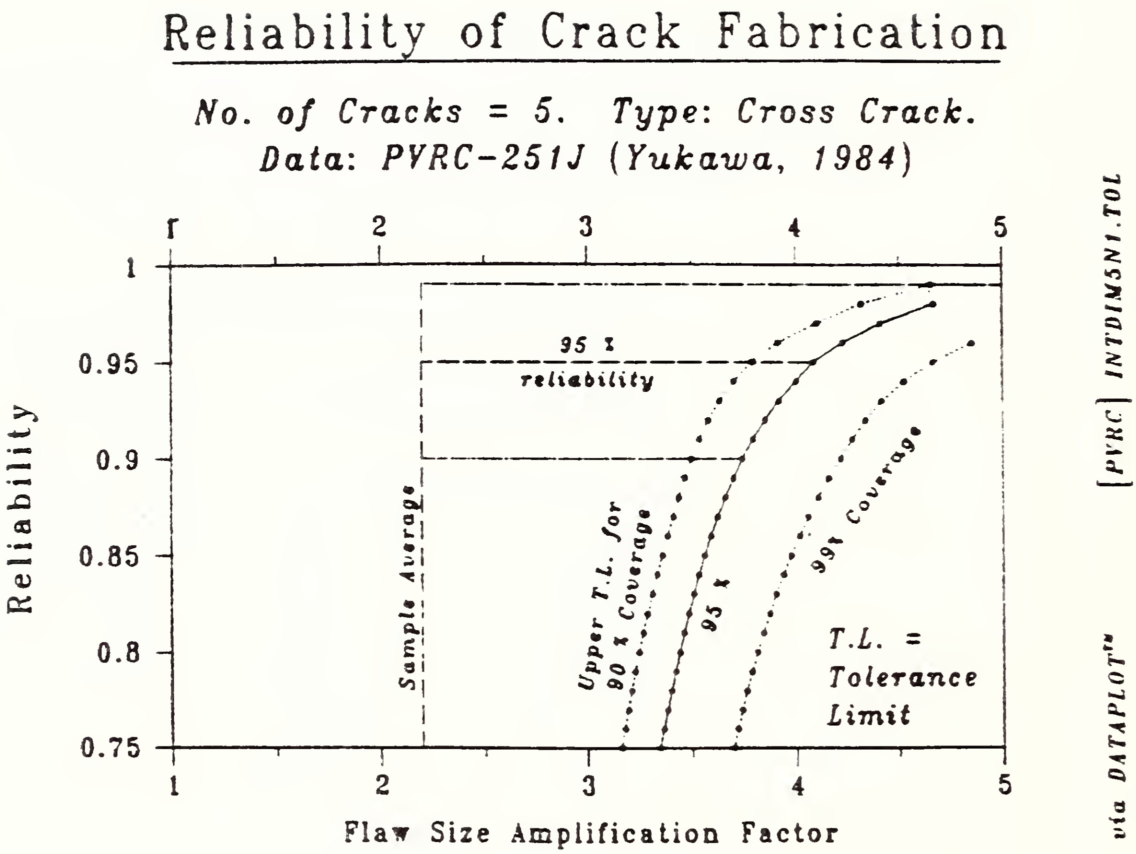



Fig. 22 Reliability of Cross Crack Fabrication as Defined by the Upper Tolerance Limit Curves for 3 coverages.

## Reliability of Slag Fabrication

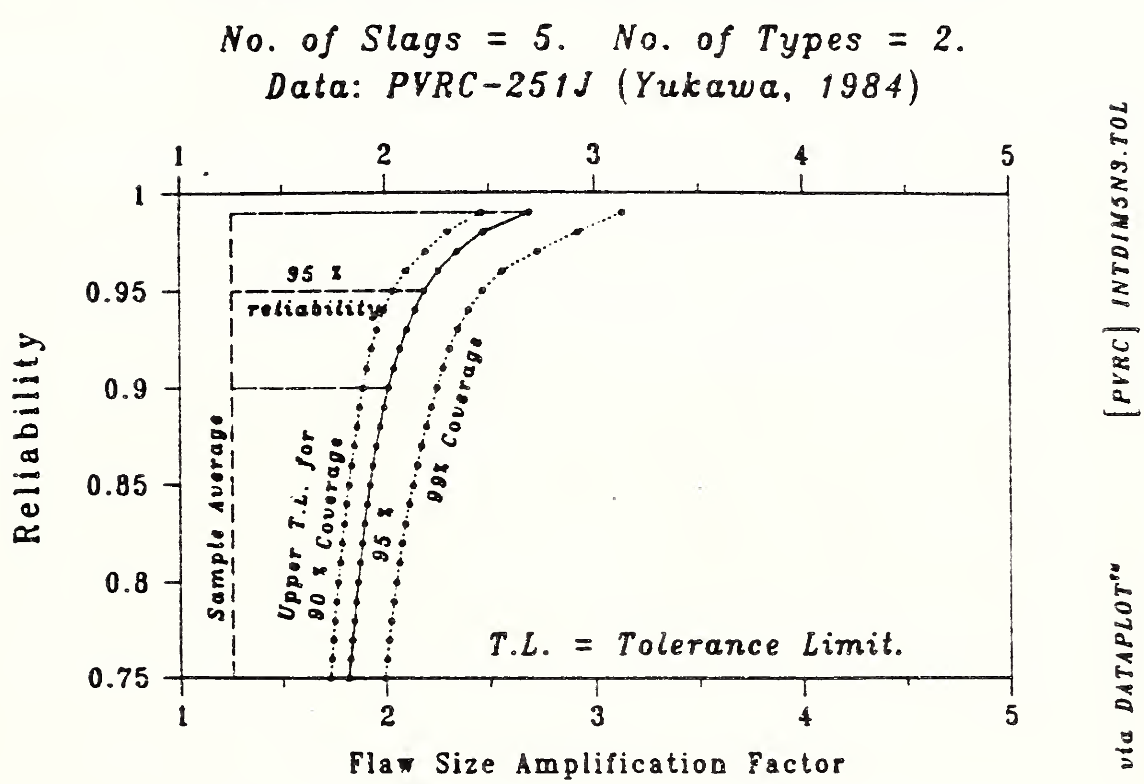



Fig. 23 Reliability of Slag Fabrication as Defined by the Upper Tolerance Limit Curves for 3 coverages.

[PVRC] UT68A.DP

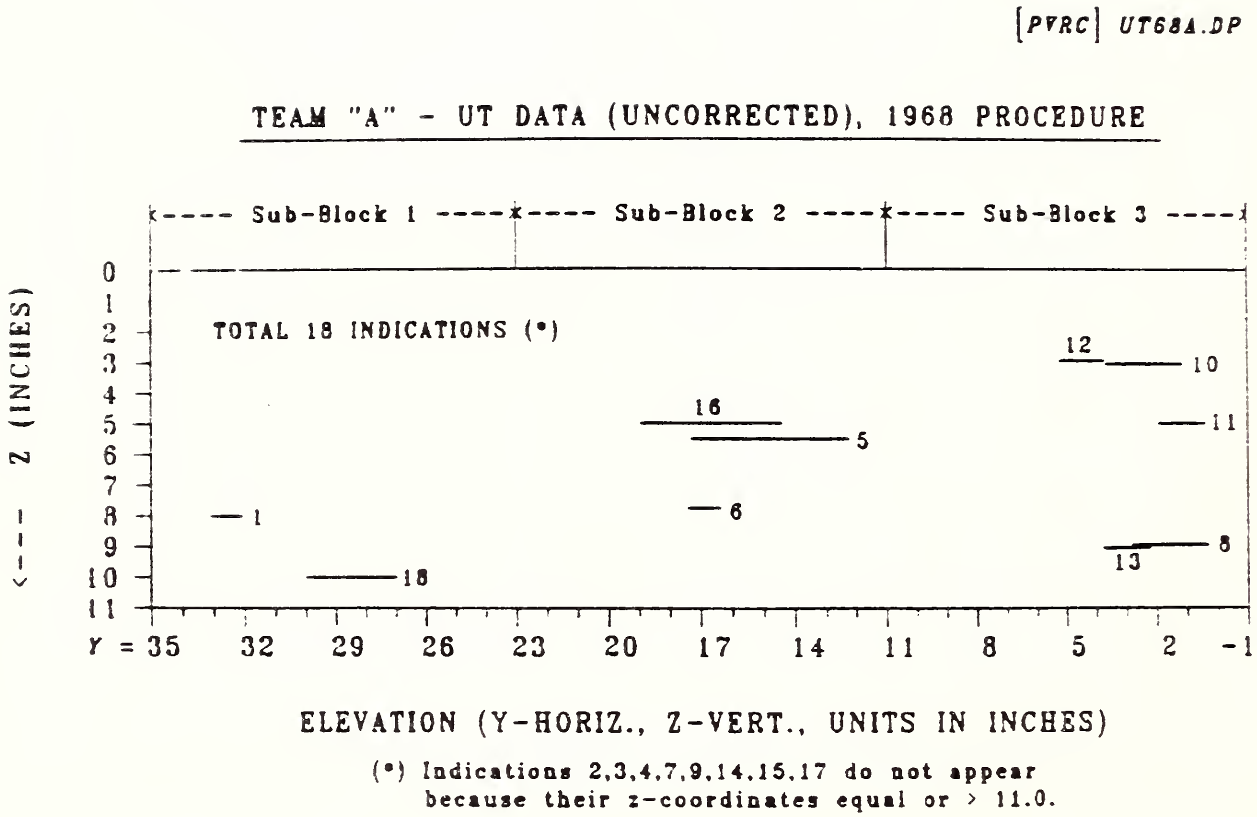



Fig. 24 Elevation of PVRC 251J showing the locations of some or all of the indications reported by Team A (Ultrasonic Testing Data, Uncorrected).

[PVRC] UT68B.DP

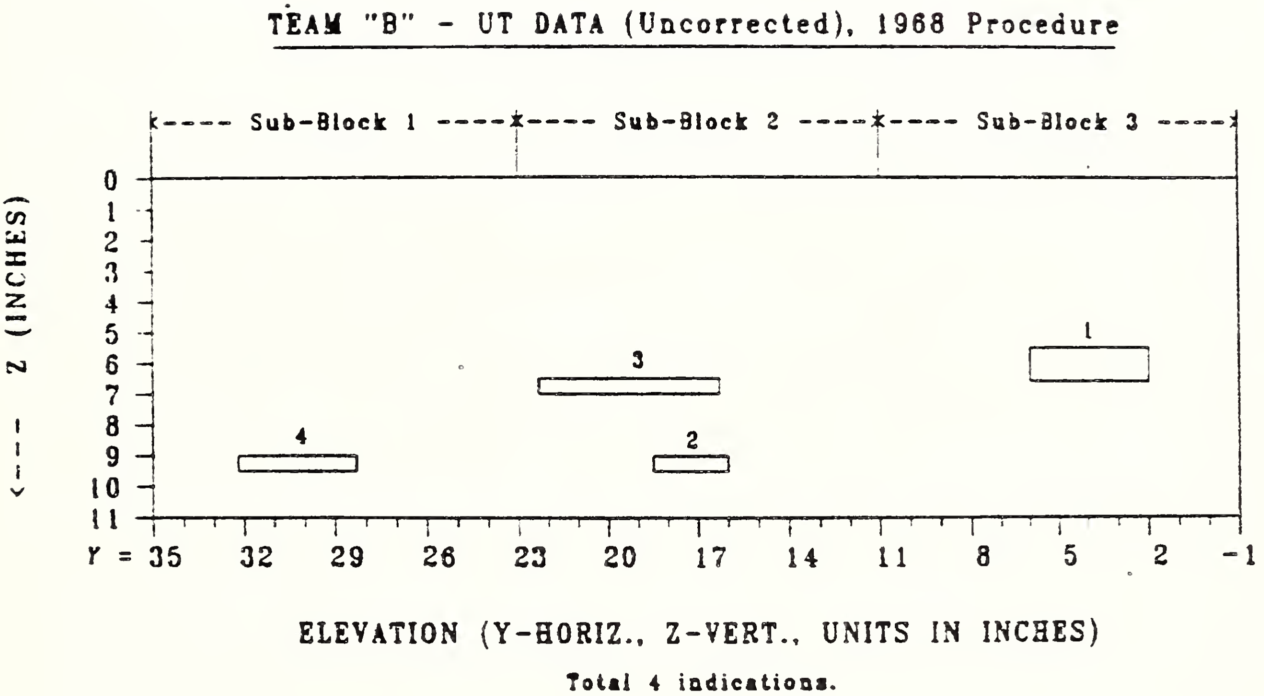



Fig. 25 Elevation of PVRC 251J showing the locations of some or all of the indications reported by Team B (Ultrasonic Testing Data, Uncorrected).

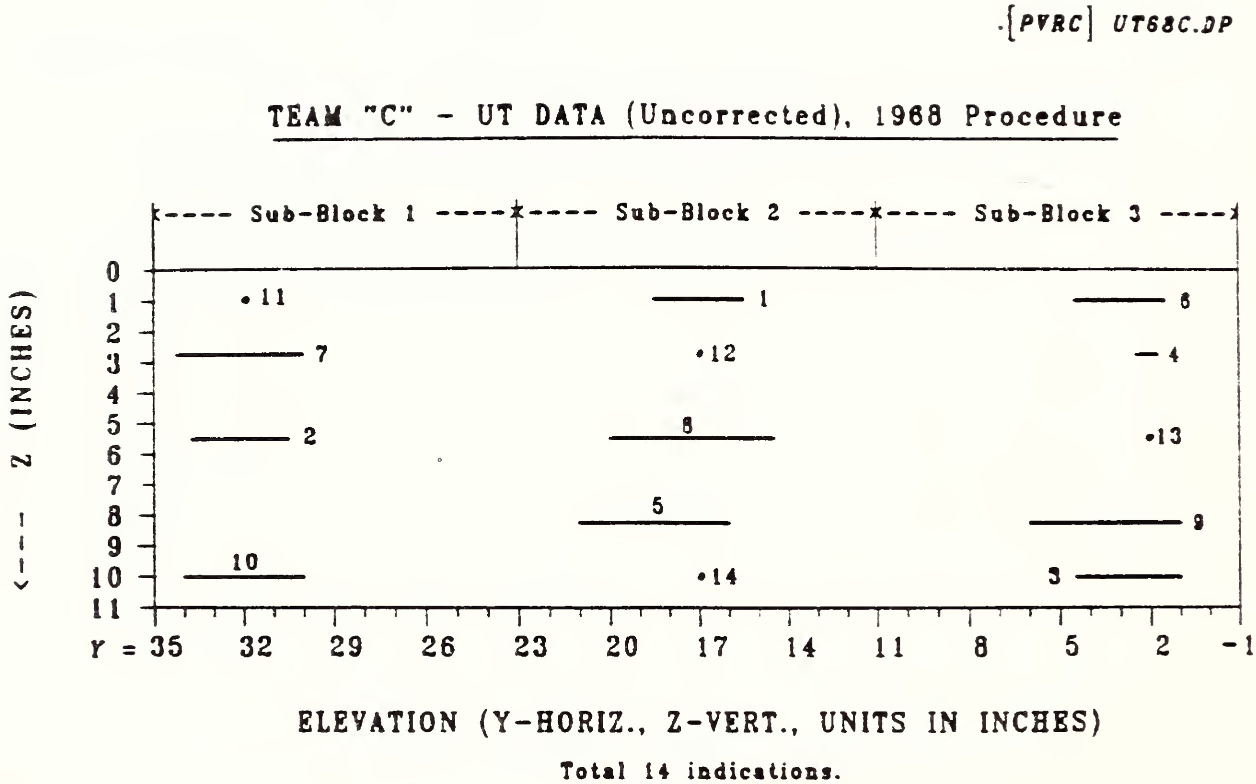



Fig. 26 Elevation of PVRC 251J showing the locations of some or all of the indications reported by Team C (Ultrasonic Testing Data, Uncorrected).

[PVRC] UT68D.DP

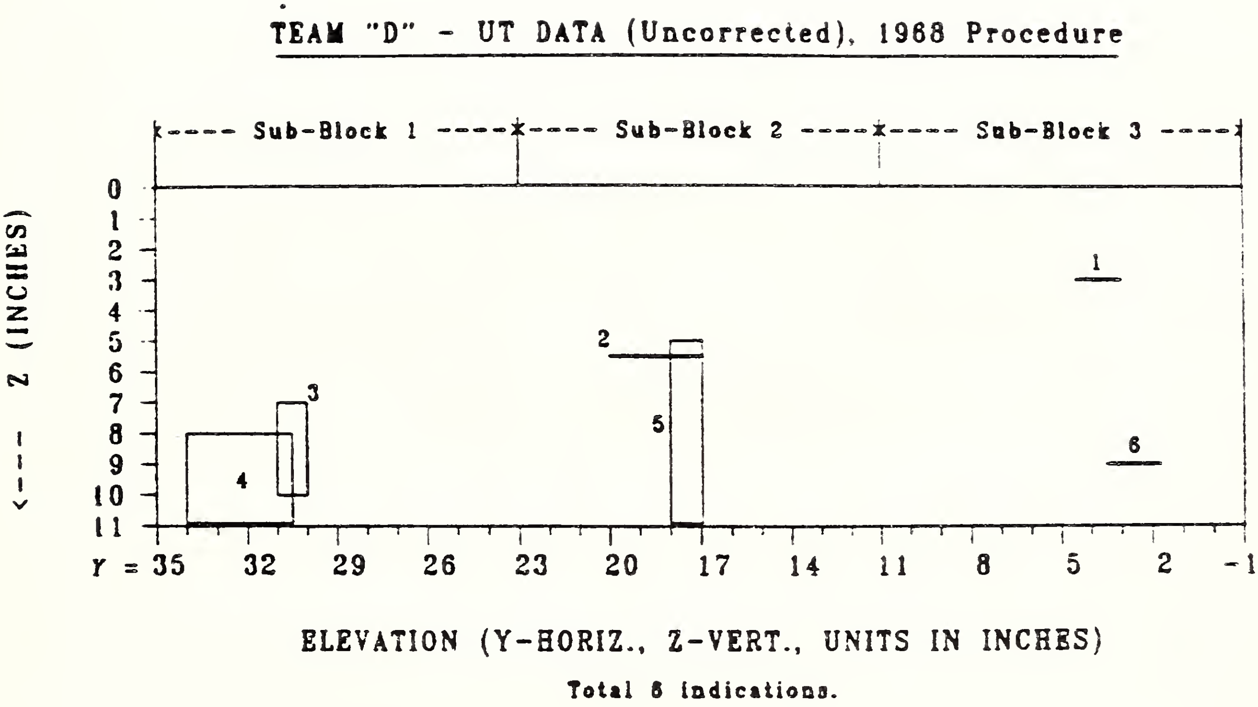



Fig. 27 Elevation of PVRC 251J showing the locations of some or all of the indications reported by Team D (Ultrasonic Testing Data, Uncorrected).

[PVRC] UT68F.DP

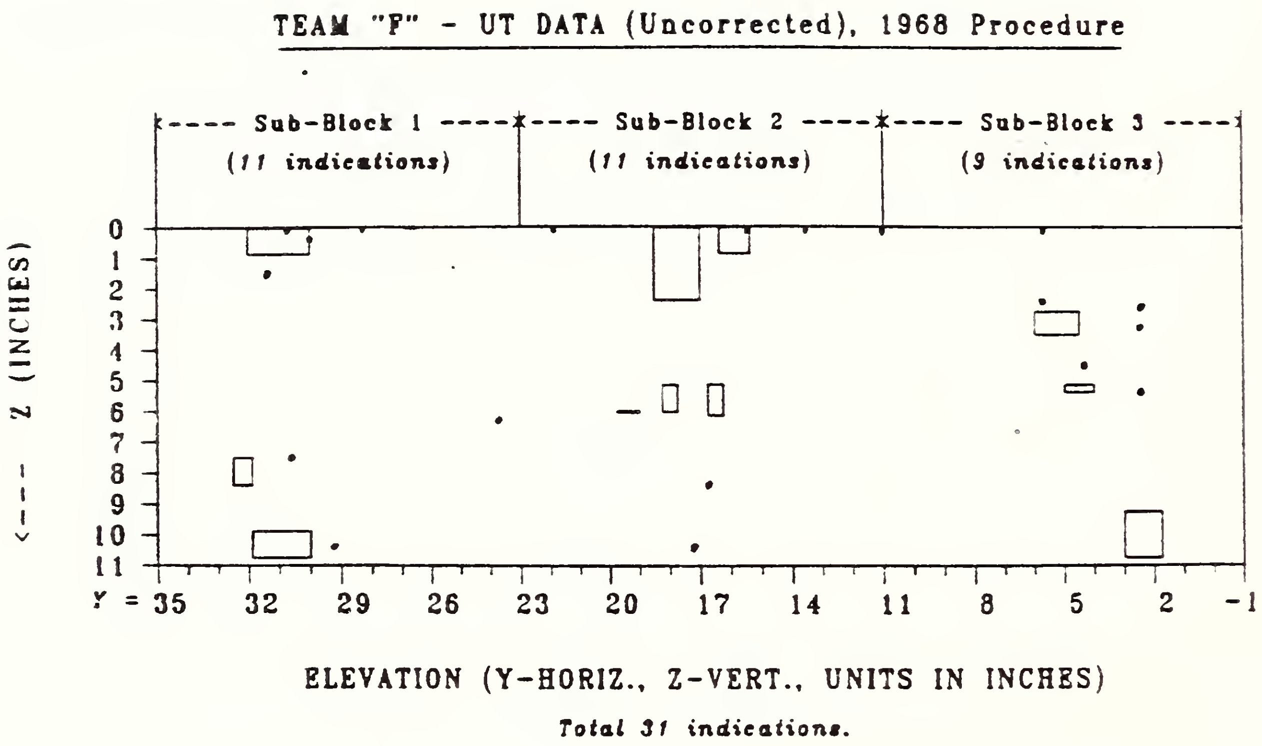



Fig. 28 Elevation of PVRC 251J showing the locations of some or all of the indications reported by Team F (Ultrasonic Testing Data, Uncorrected).

[PVRC] UT68AX.DP

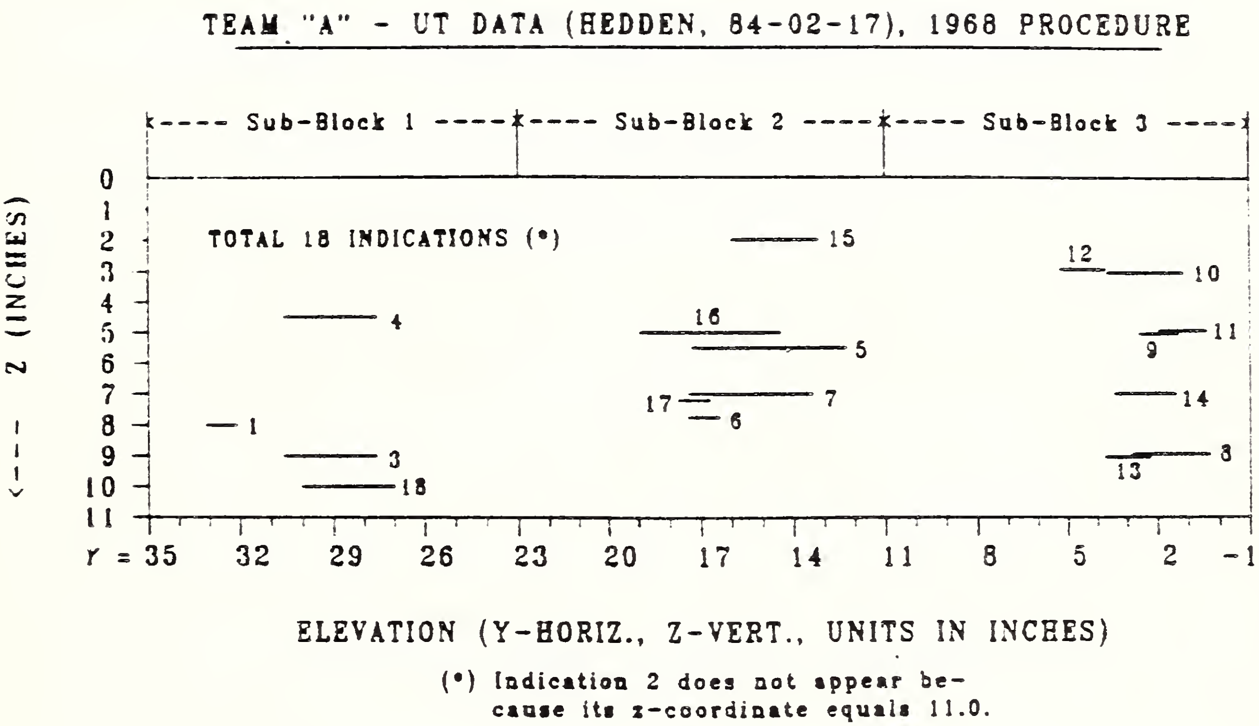



Fig. 29 Elevation of PVRC 251J showing the locations of some or all of the indications reported by Team A (UT Data, Corrected by Hedden, Feb. 17, 1984).

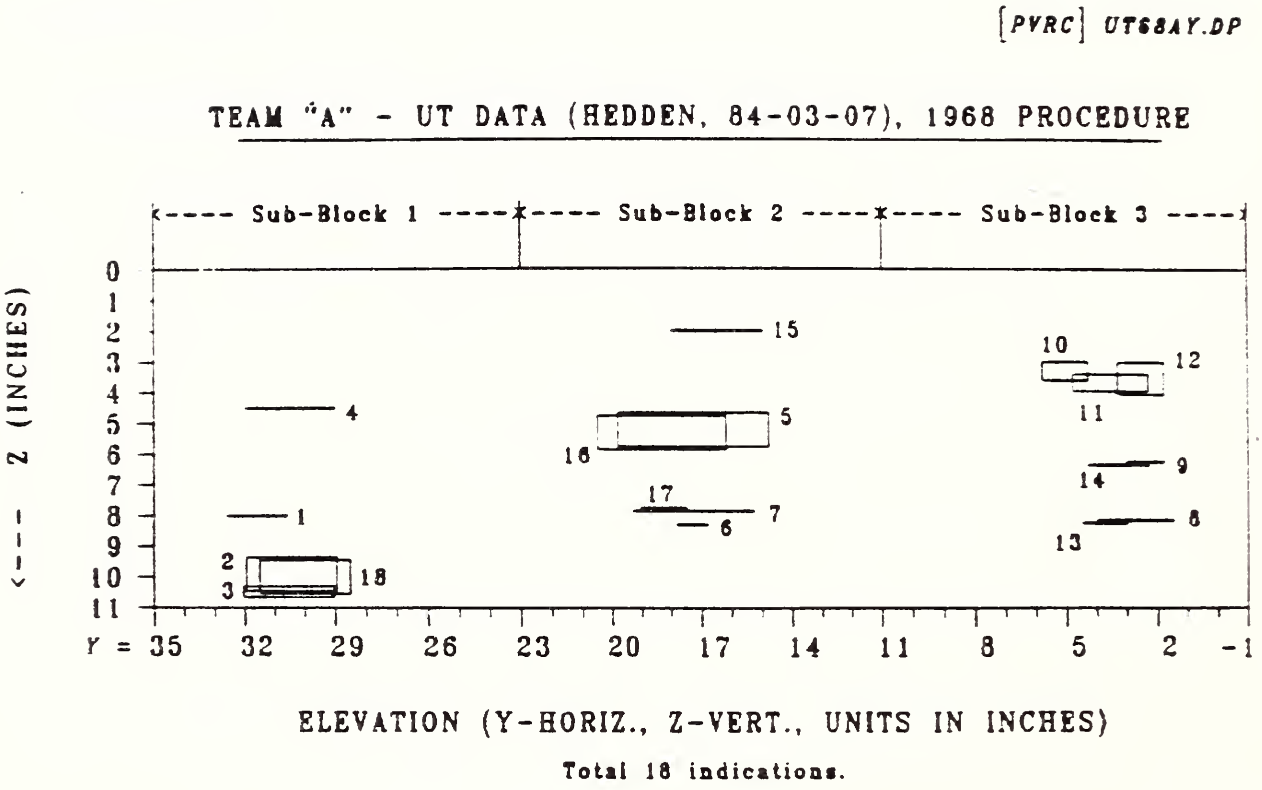
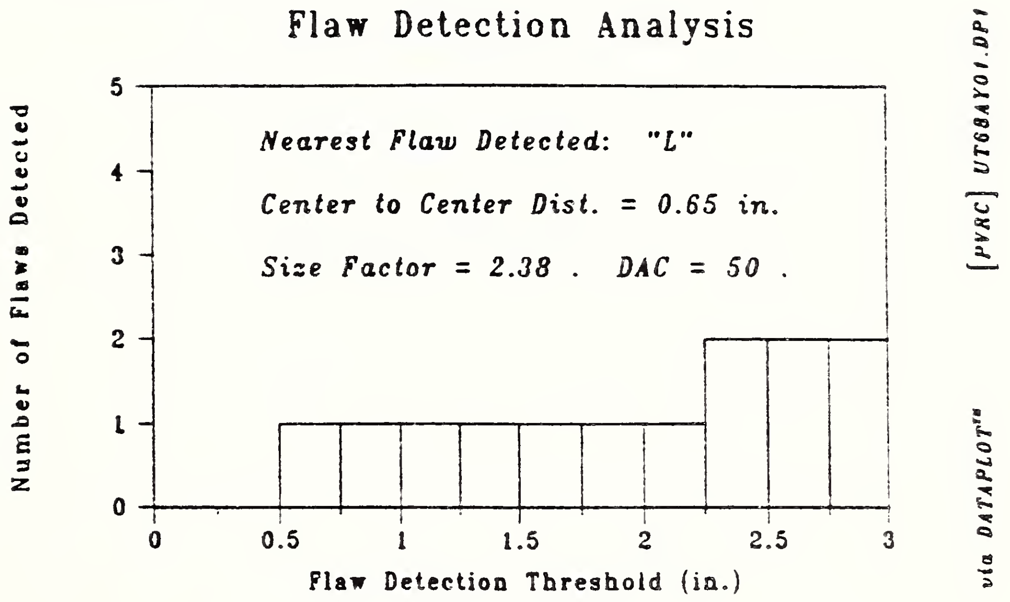



Fig. 30 Elevation of PVRC 251J showing the locations of some or all of the indications reported by Team A (UT Data, Corrected by Hedden, Mar. 7, 1984).

UT-1968-Team A: Indication #1



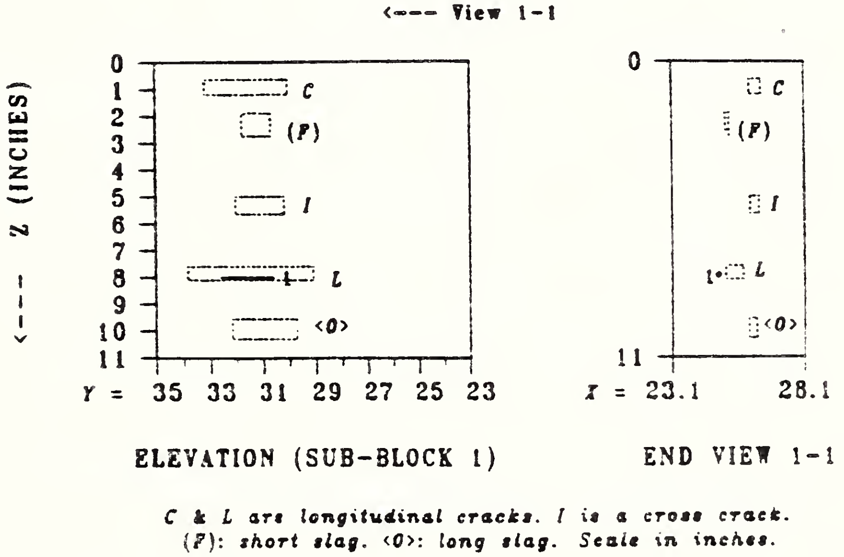




Fig. 31 Typical Result of an Automated Flaw Detection Analysis with a Variable Detection Threshold to Parametrize the Decision-Making Process.

## UT-1968-Team A: Indication #12

### Flaw Detection Analysis

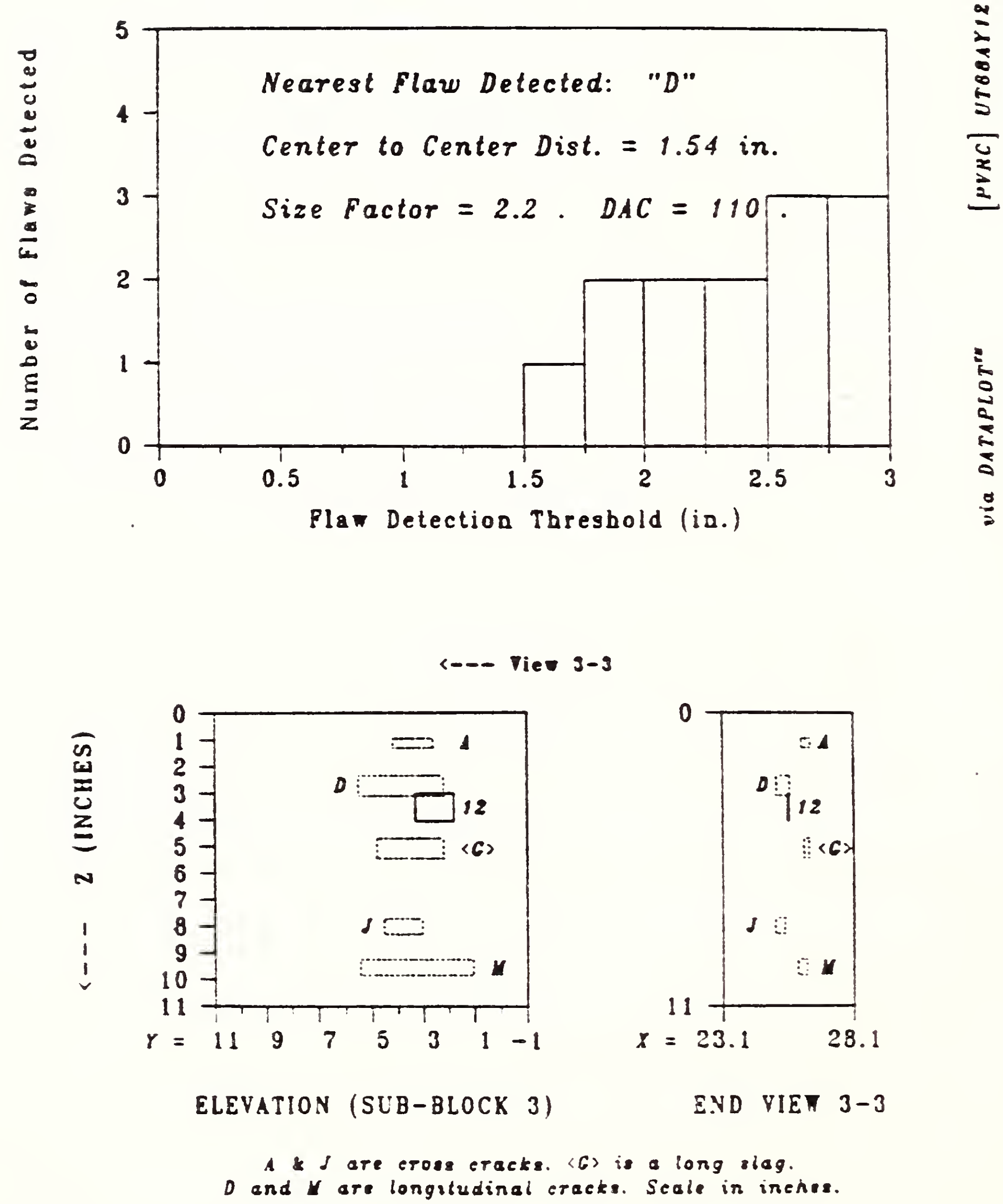
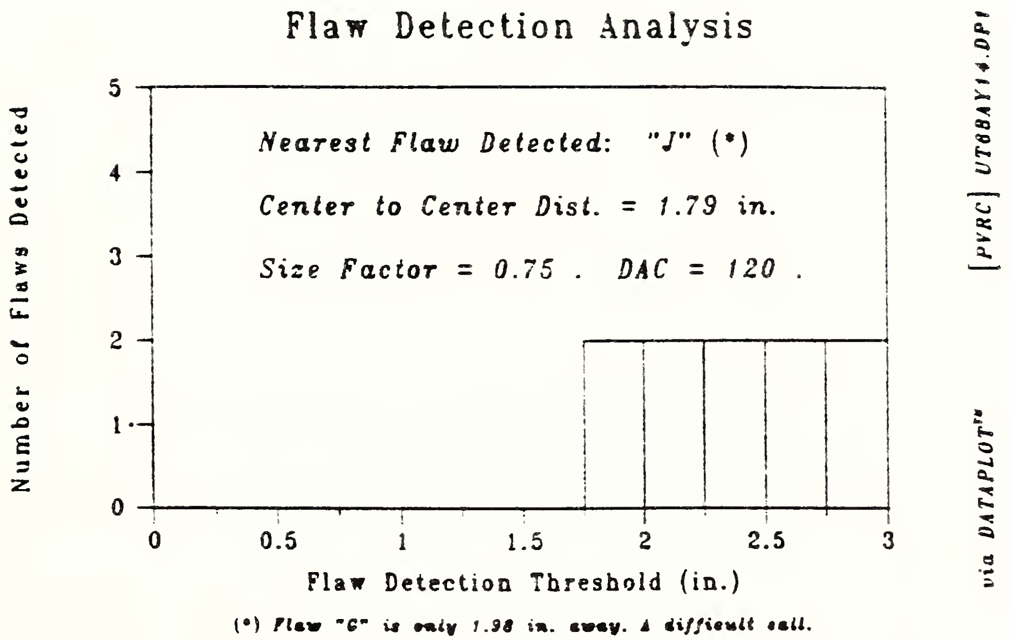



Fig. 32 A Special Case of Flaw Detection Analysis where a call for a unique detection is too sensitive to the choice of a detection threshold.

## UT-1968-Team A: Indication #14



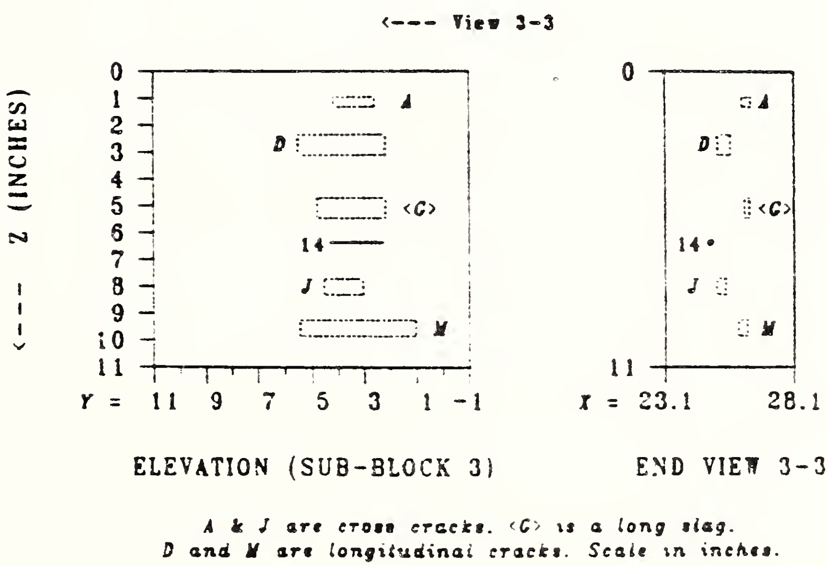




Fig. 33 A Special Case of Flaw Detection Analysis where a call for a unique detection does not exist.

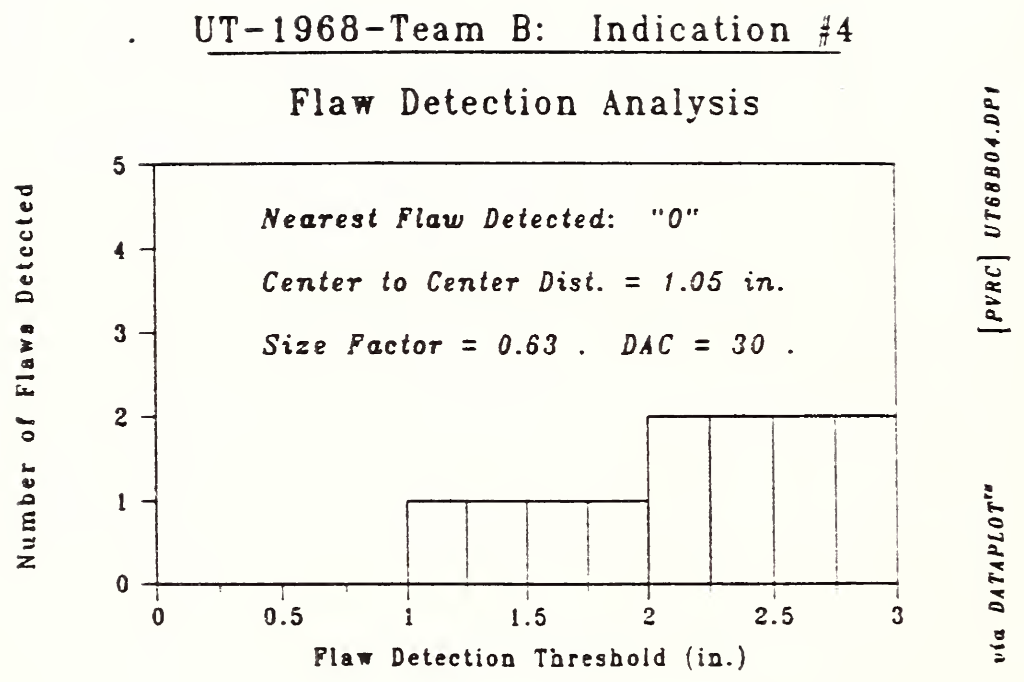



Fig. 34 A Typical Case of Flaw Detection Analysis for all indications reported by Team B (Ultrasonic Testing Data, Uncorrected).

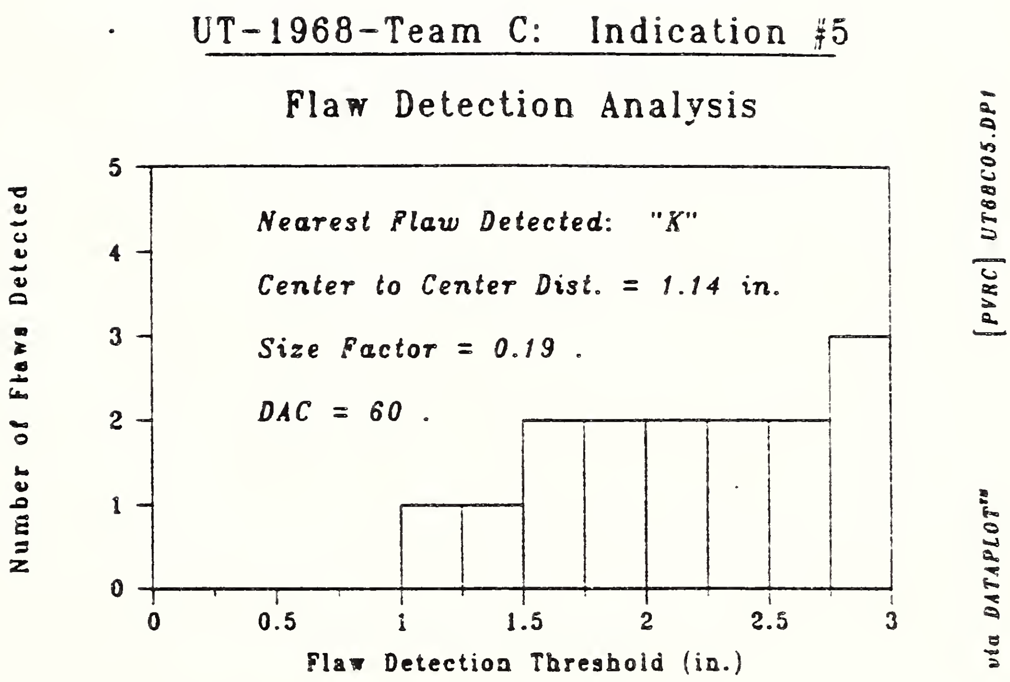



Fig. 35 A Special Case of Flaw Detection Analysis for Indications Reported by Team C, where the size factor is extremely small.

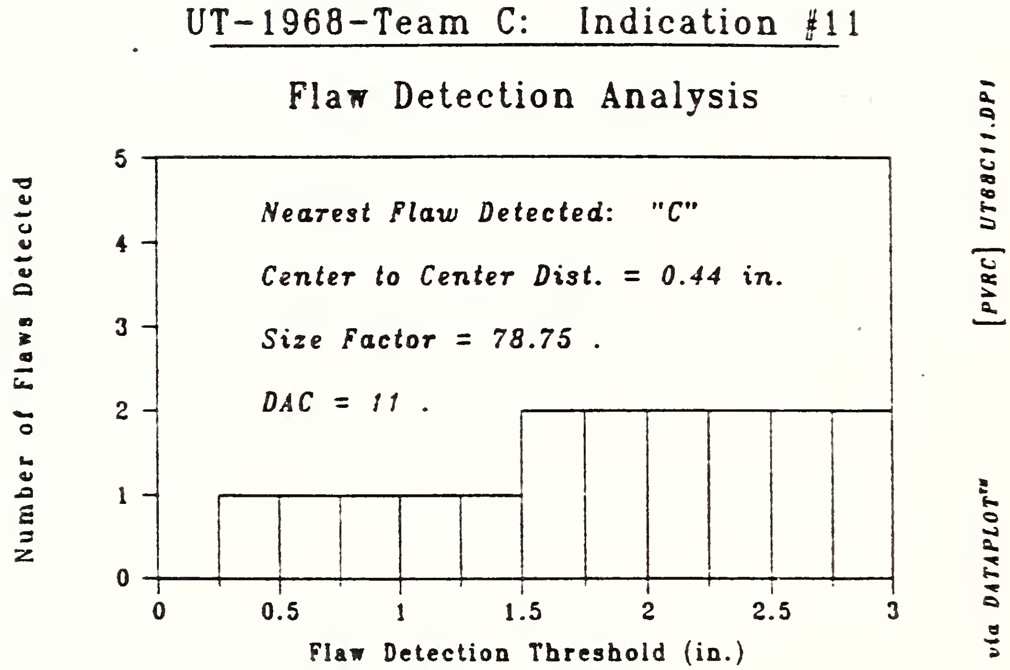



Fig. 36 A Special Case of Flaw Detection Analysis for Indications Reported by Team C, where the size factor is extremely Large.

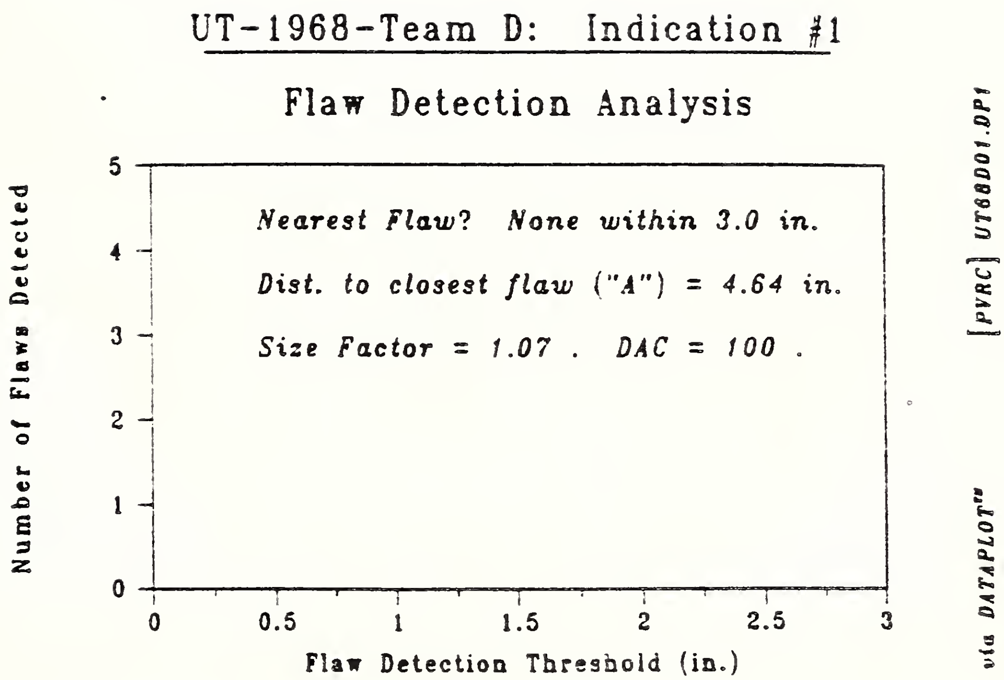



Fig. 37 A Problem Case of Flaw Detection Analysis for Indications Reported by Team D.

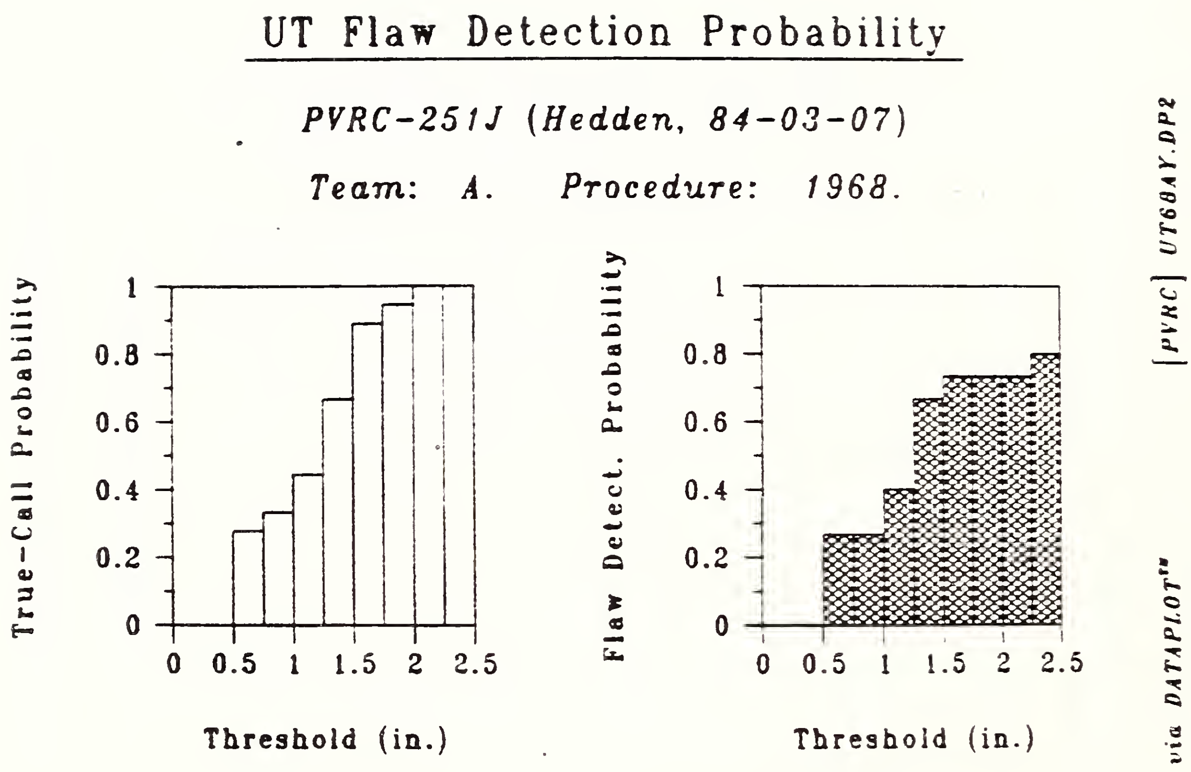



Fig. 38 True-Call and Flaw Detection Probabilities for Individual Team A (UT Data, Corrected 84-03-07).

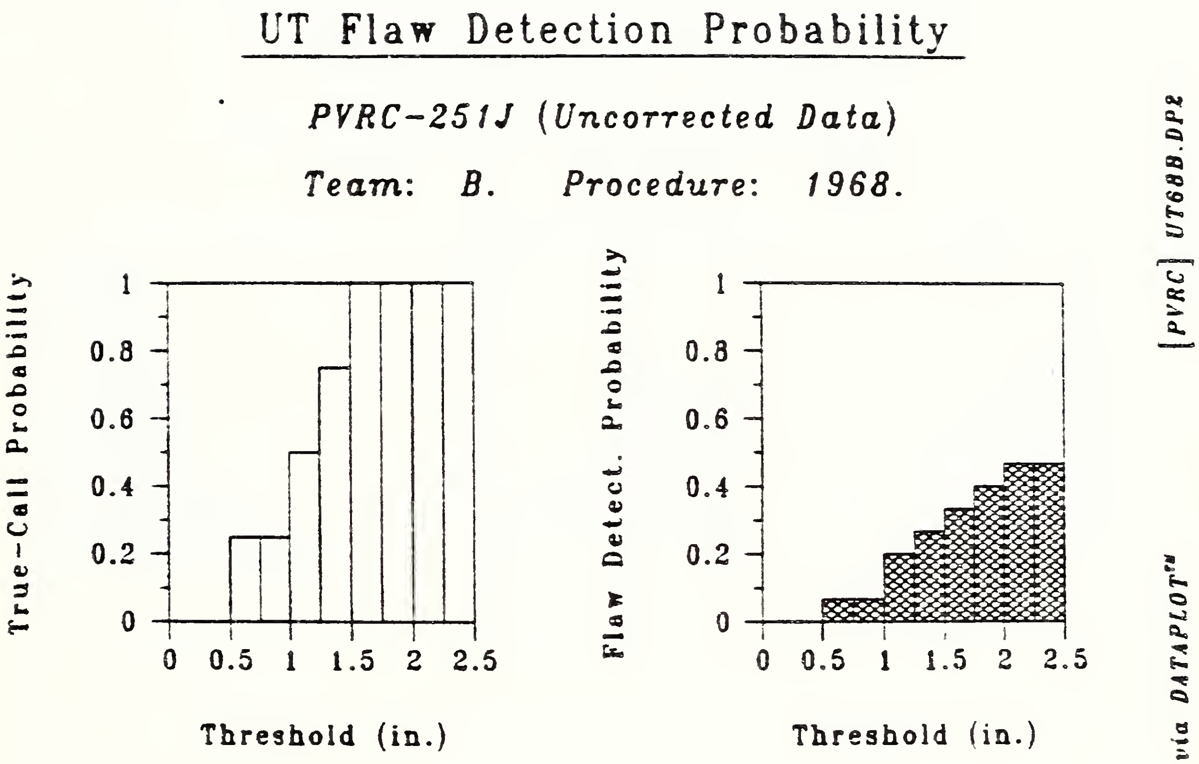



Fig. 39 True-Call and Flaw Detection Probabilities for Individual Team B (UT Data, Uncorrected).

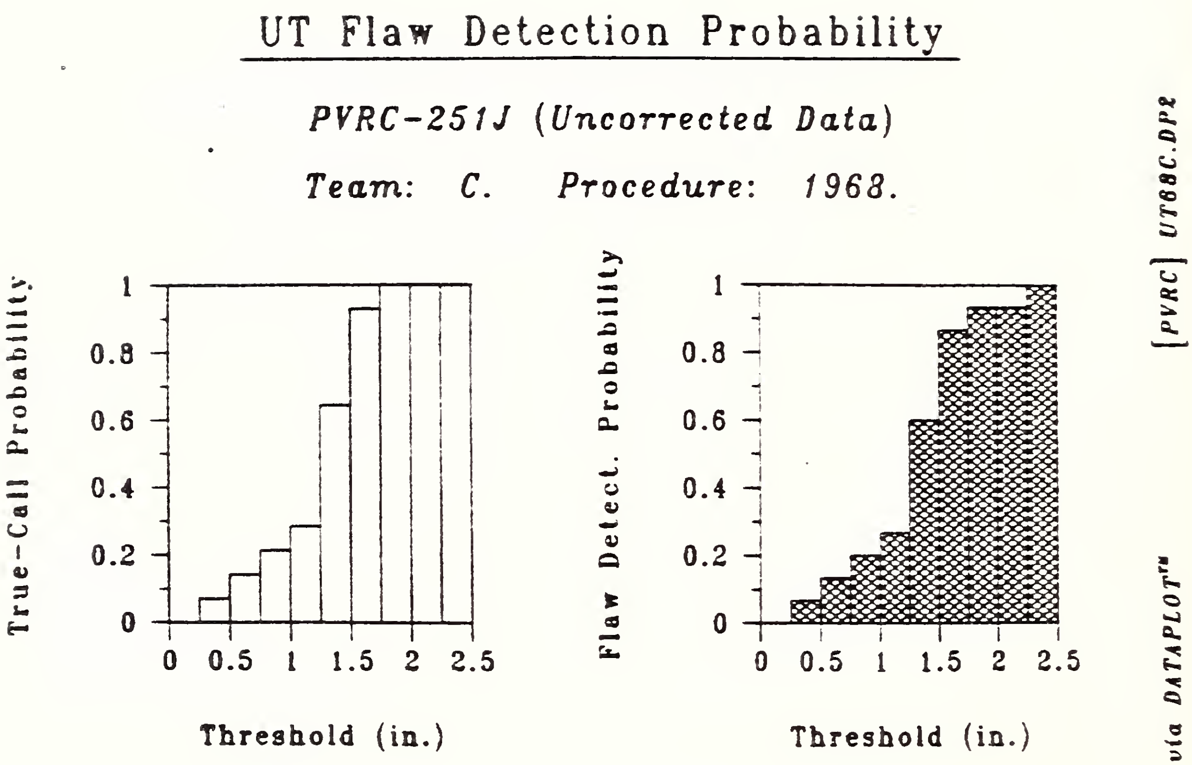
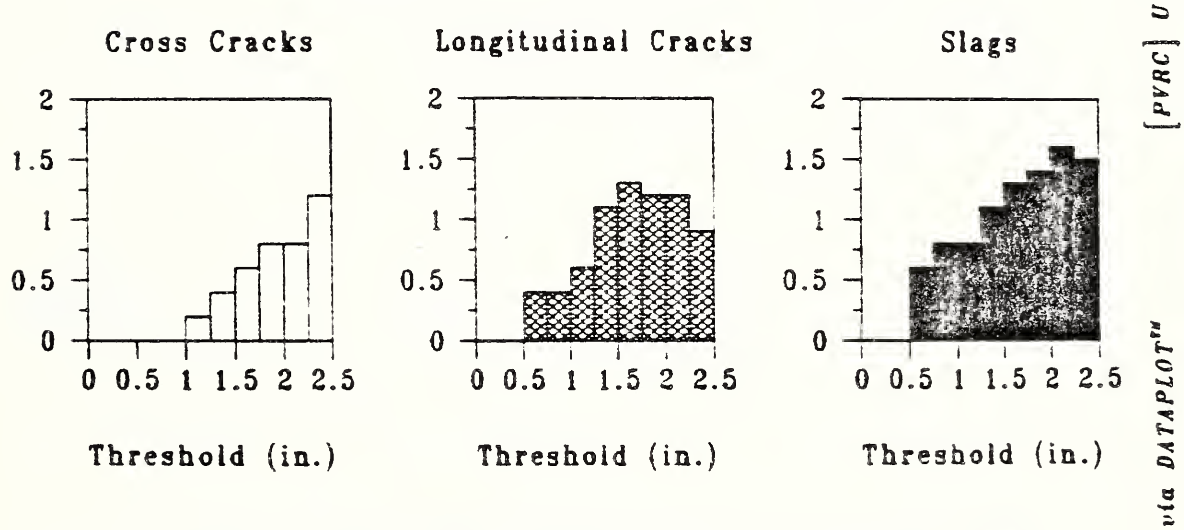



Fig. 40 True-Call and Flaw Detection Probabilities for Individual Team C (UT Data, Uncorrected).

## UT Flaw-Type Activity Index (*)

*PVRC-251J (Hedden, 84-03-07)*

*Team: A. Procedure: 1968.*




(*) No. of true calls divided by no. of possible flaws.

Fig. 41 A Performance Measure of Team A for Detection of 3 Different Types of Flaws

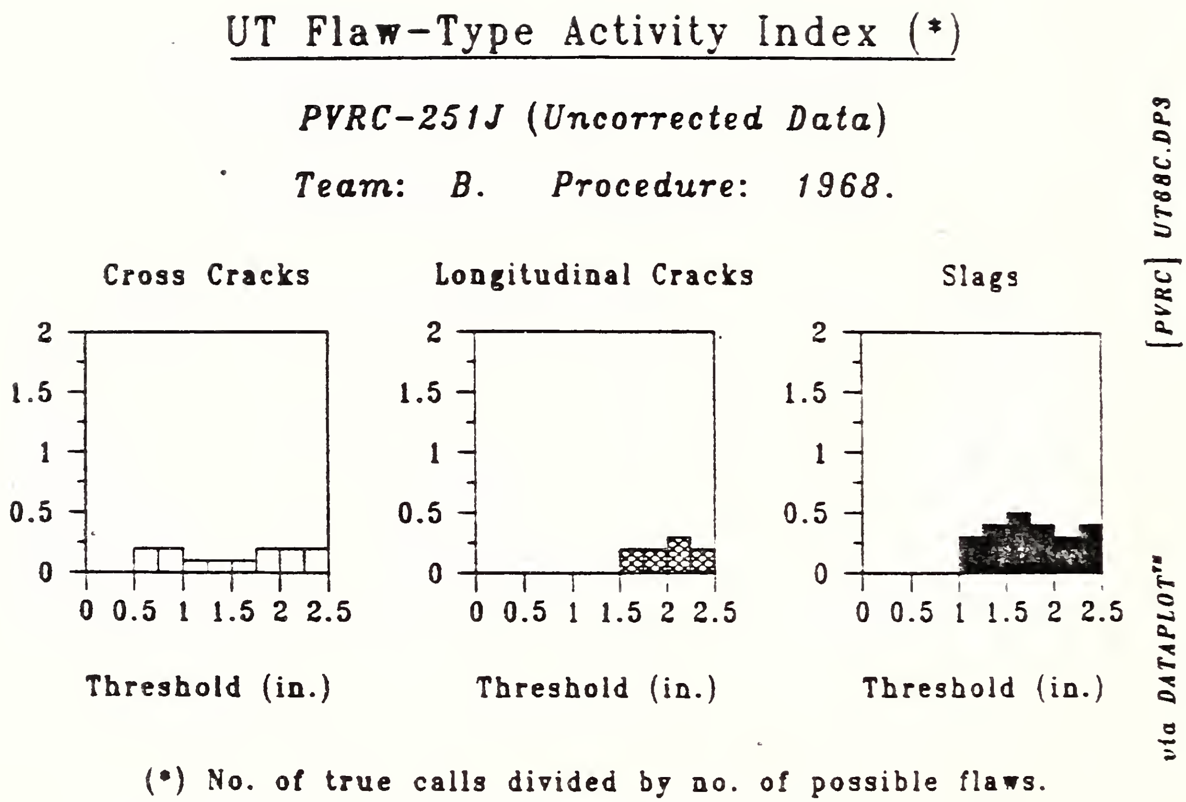



Fig. 42 A Performance Measure of Team B for Detection of 3 Different Types of Flaws

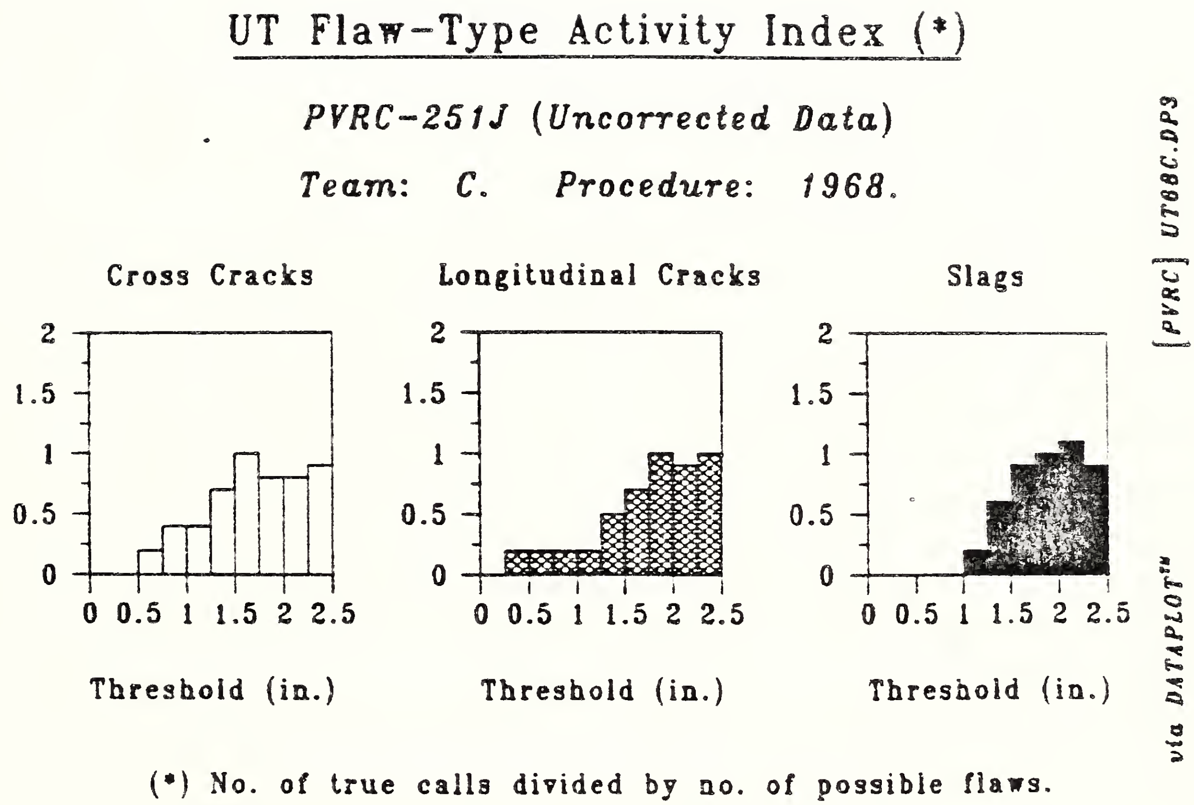



Fig. 43 A Performance Measure of Team C for Detection of 3 Different Types of Flaws

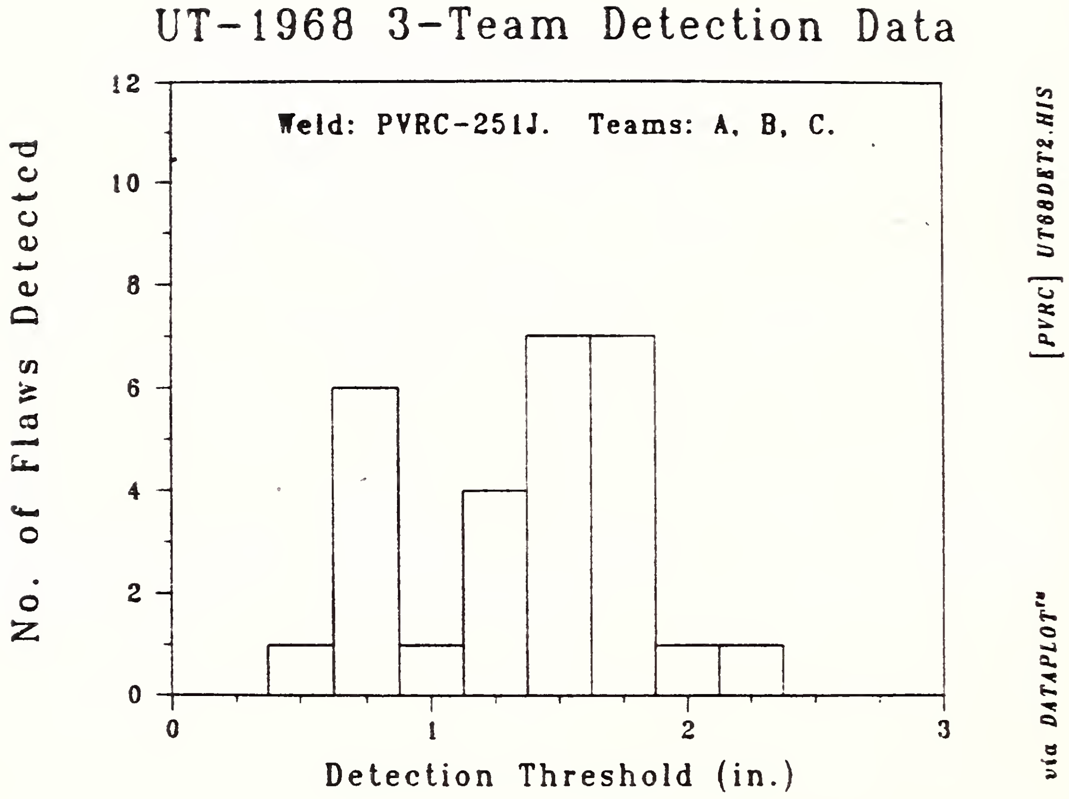



Fig. 44 Histogram of Detection Threshold for Combined 3-Team Detection Data for Reliability Modeling

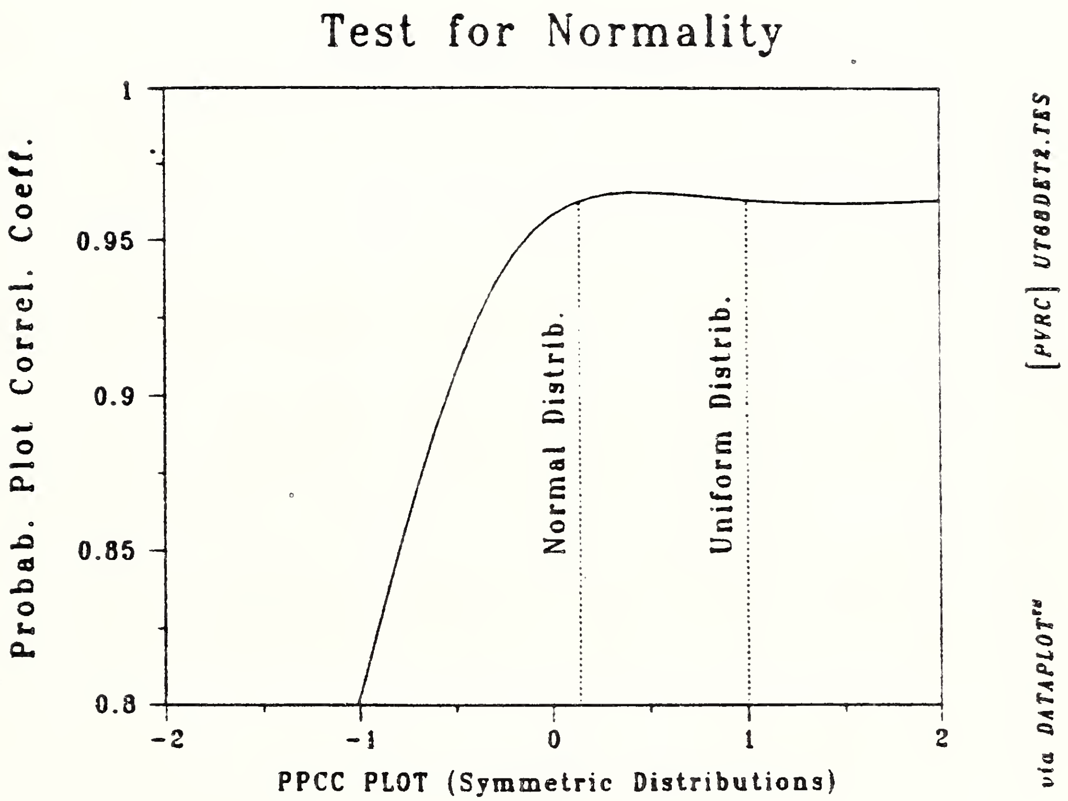



Fig. 45 Lambda Test for Symmetric Distribution Fit of the 3-Team Detection Threshold Data.

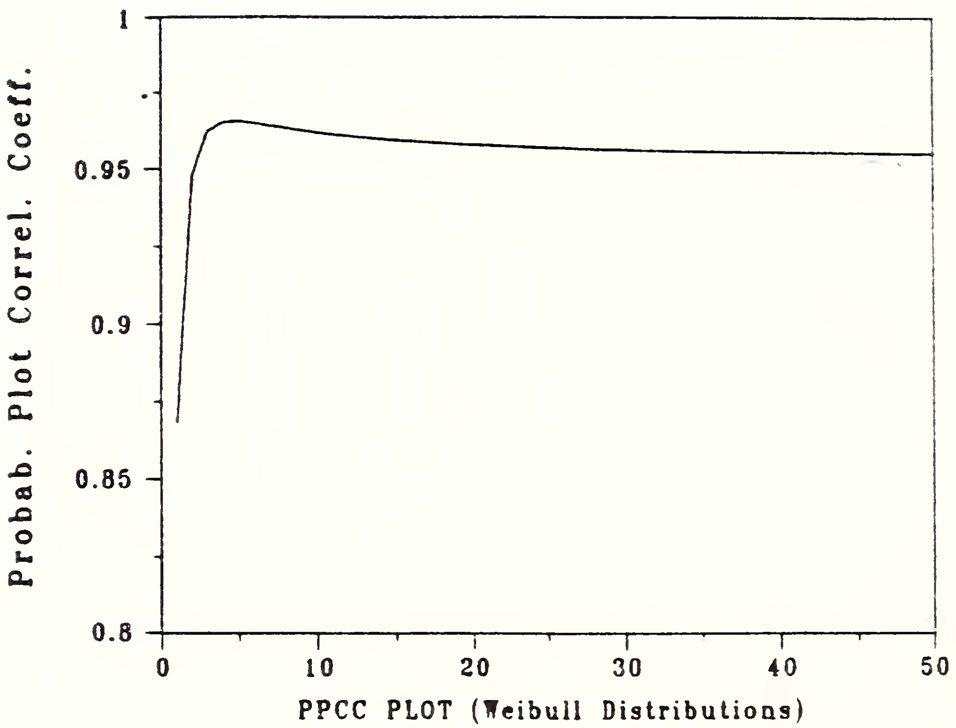



Fig. 46 Probability Plot Correlation Coefficient vs. Weibull Shape Parameter for a Test of Unsymmetric Distribution Fit.

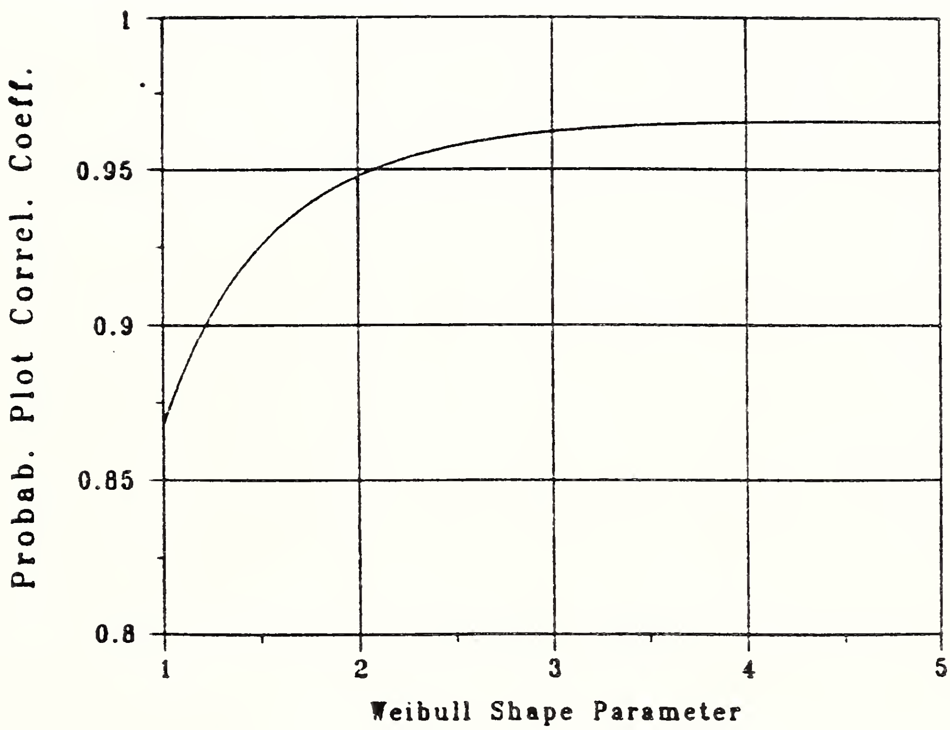



Fig. 47 An Enlarged Plot of Fig. 47 near Shape Parameter Equal to 3.6 for which Weibull approaches the shape of a Normal Distribution.

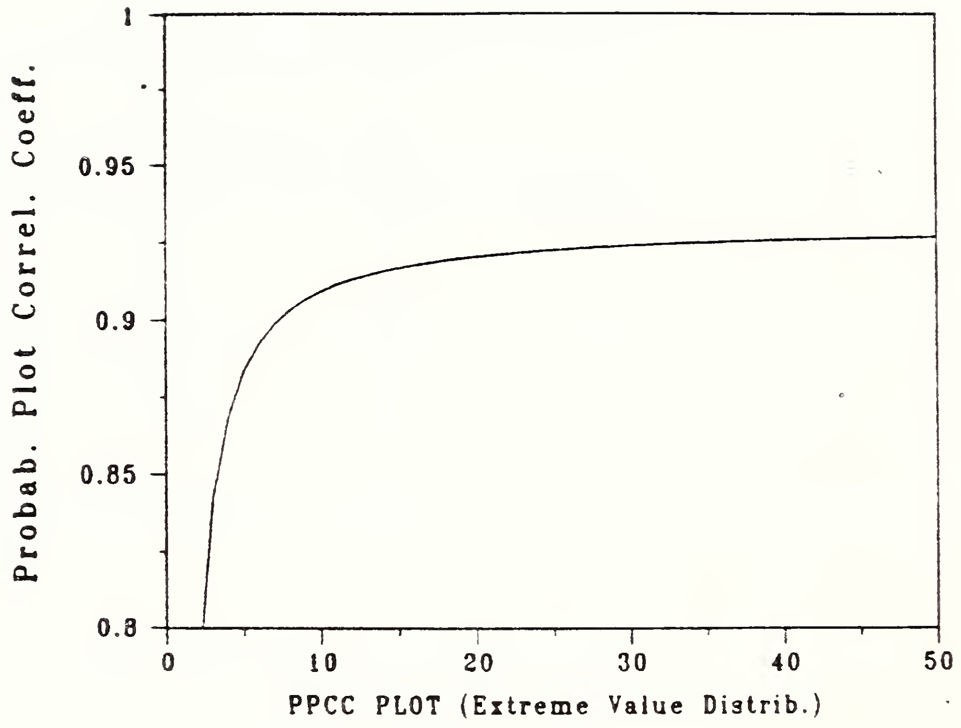



Fig. 48 Probability Plot Correlation Coefficient vs. Scale Parameter of Extreme Value Distribution as a Test for Unsymmetrical Distribution Fit.

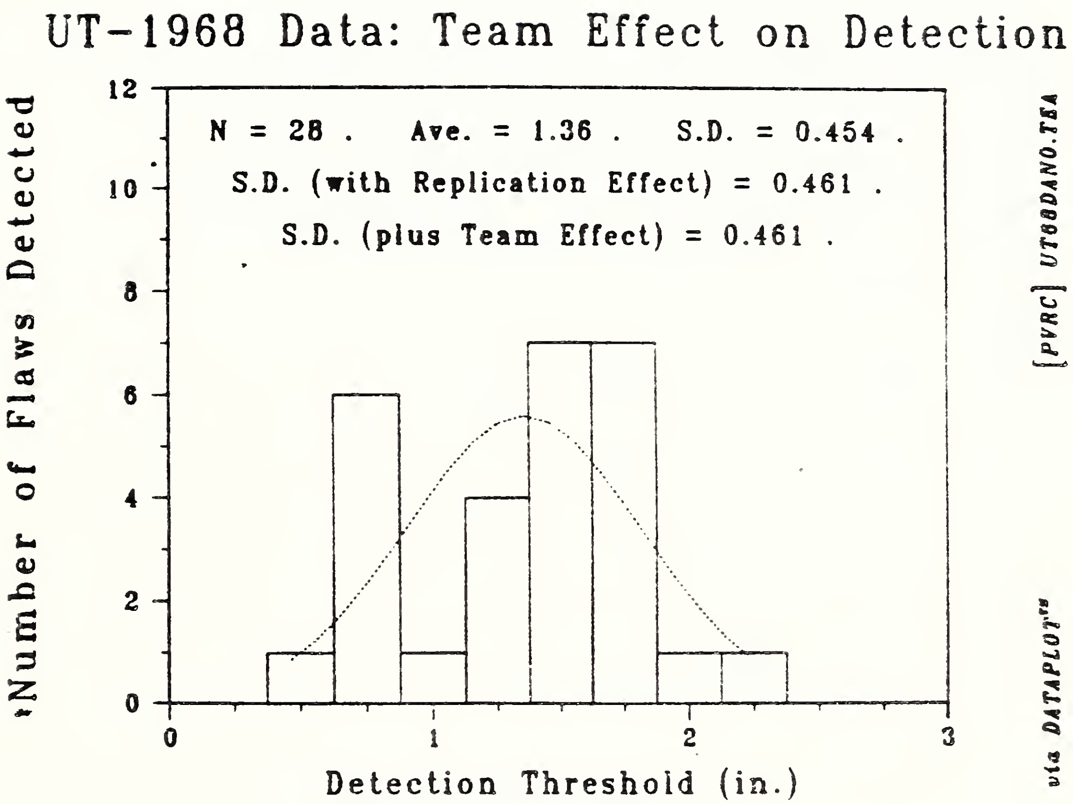



Fig. 49 Analysis of Variance (ANOVA) for Estimating Between-Team Effect on Detection for the 3-Team Threshold Data.

UT-1968 Data: Flawtype Effect on Detection

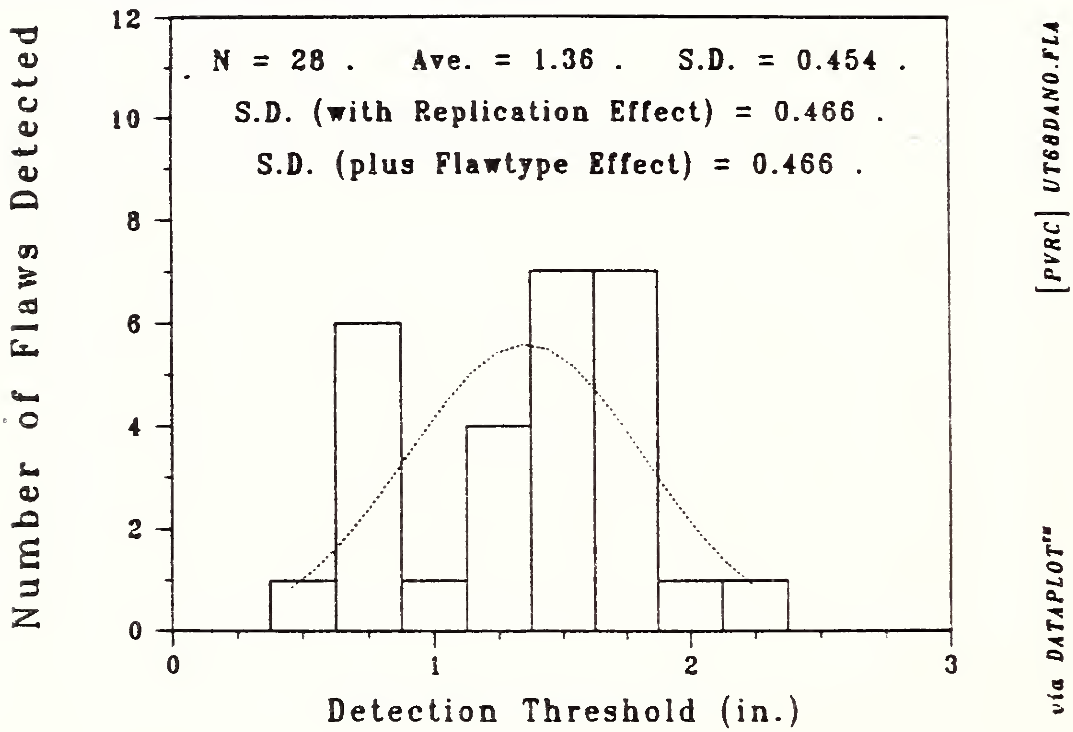



Fig. 50 Analysis of Variance (ANOVA) for Estimating Flawtype Effect on Detection for the 3-Team Threshold Data.

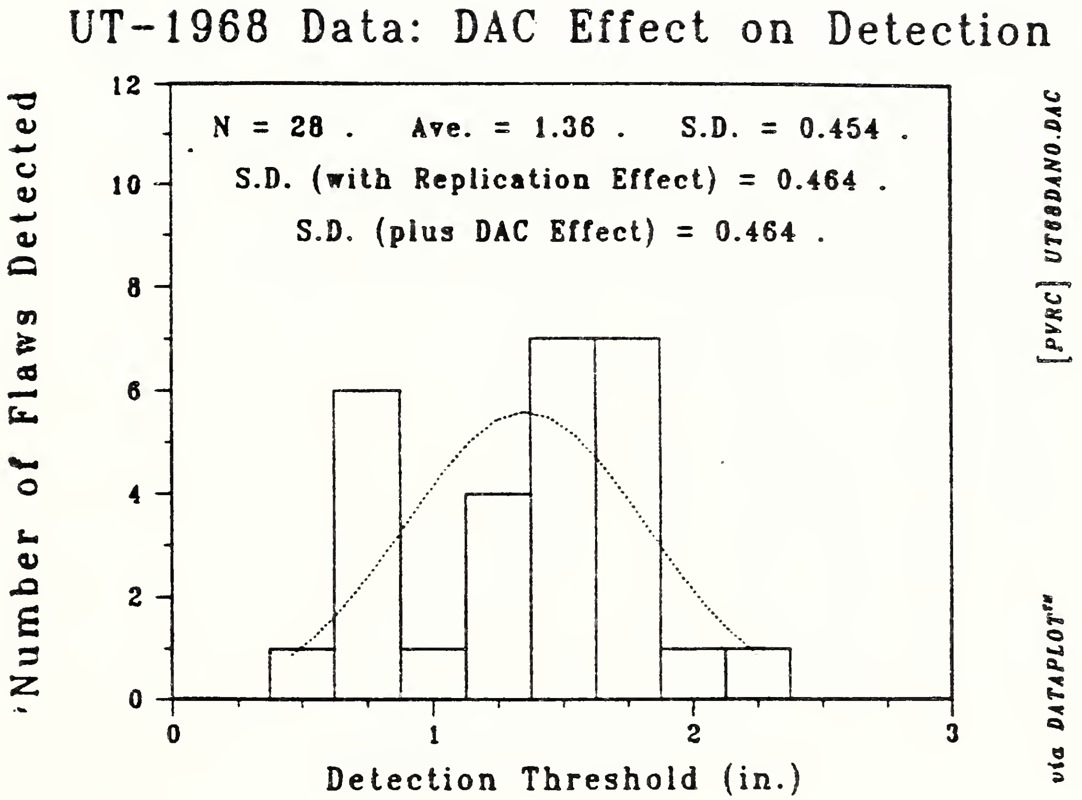



Fig. 51 Analysis of Variance (ANOVA) for Estimating DAC Effect on Detection for the 3-Team Threshold Data.

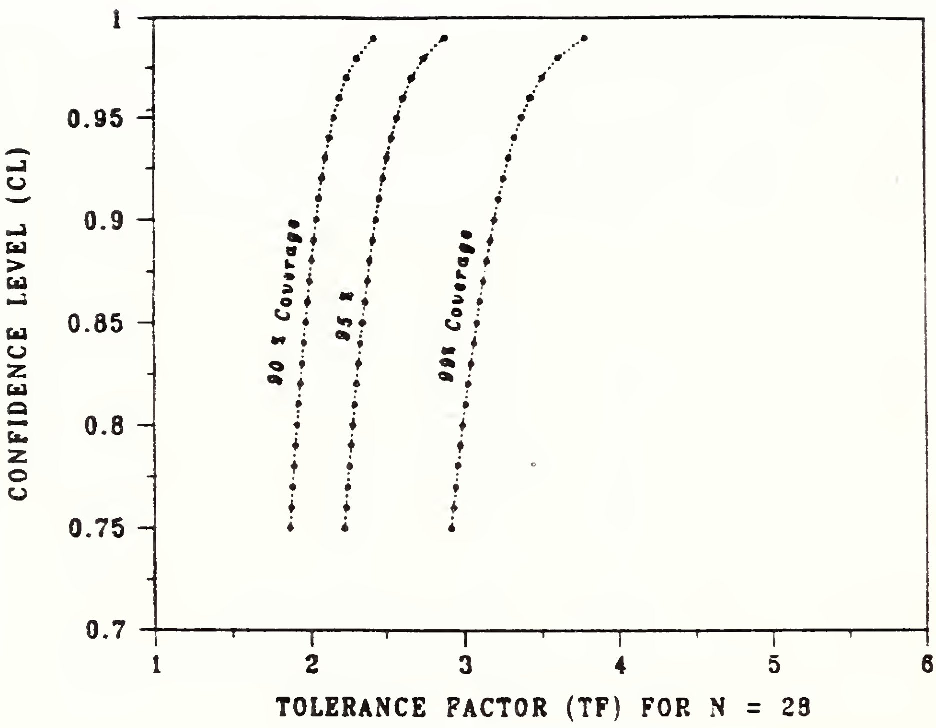



Fig. 52 Tolerance Factors (TF or K) for Sample Size N=28 and 3 population coverages (90%, 95%, & 99%), as interpolated from Tables 4,5, & 6 (Beyer, 1966).

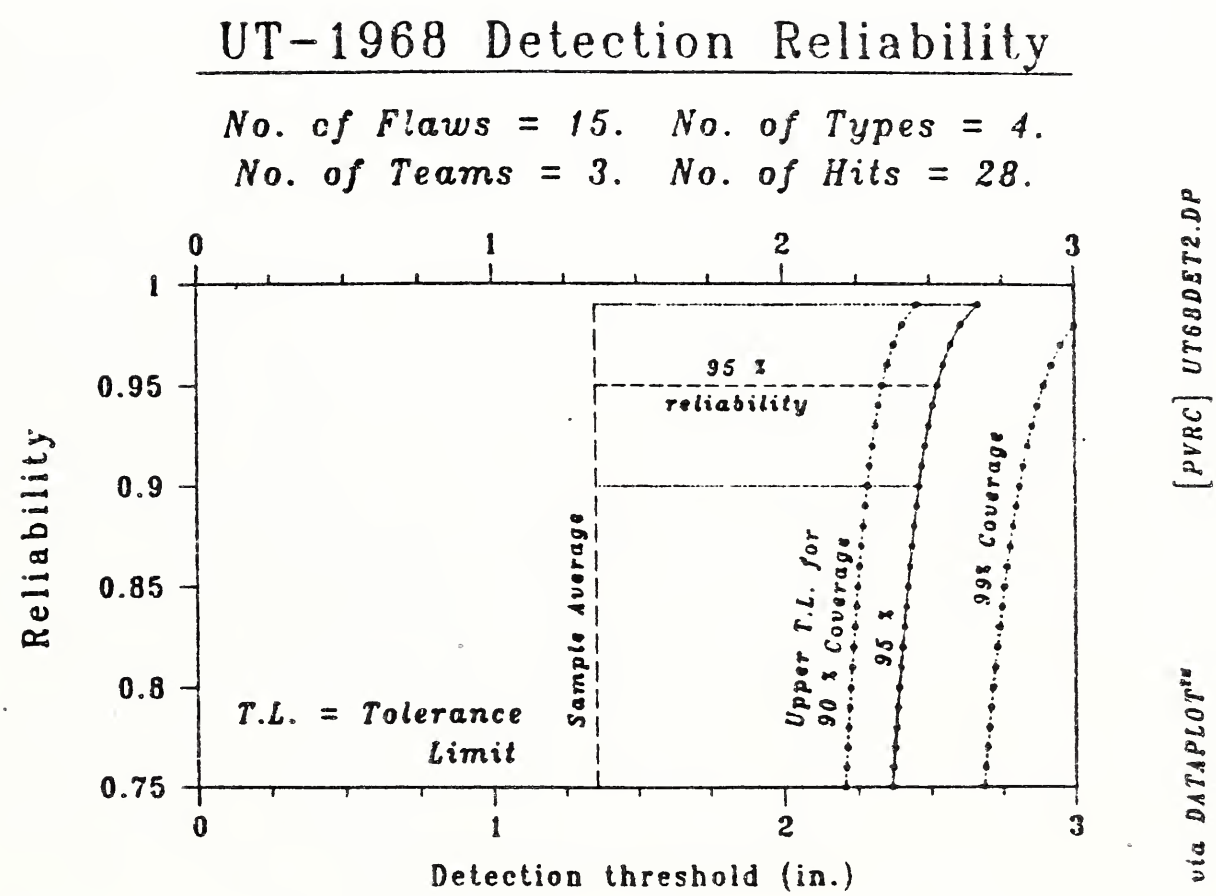



Fig. 53 Reliability of Ultrasonic Detection (1968 Procedure) of Weld Flaws As Defined by the Upper Tolerance Limit Curves for Threshold & 3 Coverages