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Inspection Reliability of Nortec-30 Eddyscan System

August 1995

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16. Abstract

The Aging Aircraft Nondestructive Inspection Validation Center (AANC) at Sandia National Laboratories is charged by the FAA to support technology transfer, technology assessment, and technology validation. A key task of the Center is to establish and apply a consistent and systematic methodology to assess the reliability of inspections through laboratory and field experiments.

Under this mandate the Nortec-30 Eddyscan inspection system was evaluated using procedures and test specimens originally developed to assess the reliability of eddy current inspections of rivet holes in a simulated Boeing lap splice. The extent and location of cracks in the upper skins were unknown to the inspector using the equipment. The results of the experiment are discussed in terms of probability of detection curves. Comparisons are made to baseline laboratory detection data obtained using other eddy current equipment.

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EXECUTIVE SUMMARY

The Nortec-30 Eddyscan inspection system is designed for testing fastener holes with the fastener in place. The Nortec-30 Eddyscan inspection system was evaluated using procedures and test specimens developed to assess the reliability of eddy-current inspections for cracks beneath fasteners. To evaluate its reliability, the system was used to inspect simulated Boeing lap splice joints. The extent and location of cracks were unknown to the inspector using the equipment.

Inspection setup was based on a reference standard with an electro-discharge machined flaw extending 0.10 inch from the edge of the countersink for the rivet head. The inspector used a subjective rating scale of 1, 2, or 3 for all signals interpreted as possible crack indications. The rating of 3 was used when the inspector was certain of a reportable flaw indication. The rating of 2 was used to indicate a reasonable certainty that a call of a flaw being present was correct. The rating of 1 was used to indicate the perception of a signal; but under the setup conditions used, there was doubt that the indication should be reported.

All flaws greater than 0.100 inch in length were detected. The largest flaw missed using the sure rating of 3 was 0.083 inch in length, whereas the smallest flaw detected was 0.037 inch in length. Probability of Detection (PoD) curves fit to this data estimate that a 0.063-inch flaw would be detected with 0.90 probability. The false call rate was 0.4 percent. Relaxing the criteria for making a call to include both the ratings of 3 and 2 resulted in a 1 percent false call rate. With this relaxed criteria the largest flaw missed was 0.06 inch in length, and the smallest flaw detected was 0.026 inch in length. The estimated PoD curve indicates that a 0.055-inch flaw would be detected with 0.90 probability.

Using the most stringent criterion (rating of 3), the Nortec-30 inspection achieved better probability of detection than was achieved in a similar experiment using a sliding probe. At the criterion level including calls rated 3 and 2, the false call rates for the Nortec-30 were comparable to that obtained with a sliding probe eddy-current inspection, but with an approximate shift in probability of detection curves of 0.01 inch.

The ability of the Nortec-30 Eddyscan system to use an "off-center" signal to give direct feedback on centering the probe was a time-saver. Lighting conditions under which the inspections were done would have forced more time to be spent in visually locating and centering rivets within a template had a pencil probe procedure been used.

1. INTRODUCTION.

The Aging Aircraft Nondestructive Inspection Validation Center (AANC) at Sandia National Laboratories is charged by the Federal Aviation Administration to support technology transfer, technology assessment, and technology validation. A key task of the Center is to establish and apply a consistent and systematic methodology to assess the reliability of inspections through laboratory and field experiments.

Under this mandate the Nortec-30 Eddyscan inspection system was evaluated using procedures and test specimens originally developed to assess the reliability of eddy-current inspections for cracks beneath fasteners. The Nortec-30 Eddyscan inspection system is designed for testing fastener holes with the fastener in place. To evaluate its reliability, the system was used to inspect simulated Boeing lap splice joints. The extent and location of cracks in the upper skins were unknown to the inspector using the equipment. The results of the experiment are discussed in this report in terms of probability of detection curves. Comparisons are made to baseline laboratory detection data obtained using other eddy current equipment.

This report is organized into four sections. Section 1 contains a brief product description. Section 2 discusses the conditions surrounding the experiment and the setup procedures followed in performing the experiment. Results of the inspection are presented in the form of probability of detection (PoD) curves and relative operating characteristic (ROC) curves in Section 3. A summary and a discussion of the results are given in section 4.

2. PRODUCT DESCRIPTION.

The following brief description of the Nortec-30 Eddyscan system is condensed from product description information available from Staveley Instruments, Inc. This description is meant to reflect the basic technology and capabilities of the instrument. It is not a complete description of all the capabilities of the instrument.

The Nortec-30 Eddyscan System is designed for testing fastener holes with the fastener in place. It consists of a portable instrument with an accompanying small hand-held scanner. The instrument uses pulsed eddy current techniques and a broadband Hall effect sensor.

The scanner is centered over the fastener during the inspection. The scanner rotates the Hall effect sensor and the driving coil about the fastener. Eddy currents are induced by the coil into the test surface. The induced signal is a sharp-edged magnetic pulse that provides excitation for a wide range of frequencies. Due to phase velocity effects, the lower frequency components propagate through the material at slower rates than do the higher frequency components.

As a result of the differences in propagation times, effects from defects that are shallower appear earlier on the detected waveform. A "gate" of a certain width is set to start a certain time after the start of each pulse. The width and start time of the gate are set by the user and are determined with test standards. The outputs for a particular gate are arranged sequentially. If there are no flaws and the scanner is perfectly centered, the resulting outputs would form a straight line. The presence of a flaw will alter the signal as the Hall sensor passes. This will cause a "bump" to appear in the baseline signal. By adjusting the gate parameters and the gain applied to the signal, the instrument sensitivity can be altered for both flaw depth and size.

If the Hall sensor is not exactly centered over a circular fastener, the distance between the edge of the fastener and the sensor will vary sinusoidally. If the changes in distance are relatively small, the off-center probe signal will also be roughly sinusoidal. The frequency of the sine wave will be the rotation frequency of the scanner. Thus, when the scanner is close to being centered, the remaining off-center signal can be removed by subtracting the appropriate sine wave.

The "off-center" signal is not totally discarded. It is used to aid in positioning the scanner over the fastener. First the signal is filtered. Then the phase angle of the peak is used to derive off-center direction and the amplitude of the signal is used to determine the distance from the center. This information is then used to drive a cross hair on the display showing relative positioning.

The instrument has been designed to have three (3) modes during operation. These are:

1. Free-running operation
2. Search for center
3. "Frozen" analysis display

In the free-running operation the raw data from the scanner are displayed on the screen. The off-center data and centering cross hairs are also displayed. Displays are updated as the scanner moves across a fastener. Upon pressing the [TEST] button on the instrument, the search for center mode is entered. This mode differs from the free-running mode in that the instrument is checking that the cross hair is less than a certain distance from the origin. "Close enough" is represented by a circle on the cross hair display. The actual off-center distance is determined by the gain setting on the centering gate.

The instrument will switch to a frozen analysis display once the cross hair stays in the circle for about 1 second. It is at this time that the off-center data are removed from the signal and the processed data are shown on the screen. A threshold can be set as a percentage of full scale. If an inspection results in a signal that exceeds this threshold then an alarm will alert the operator.

3. EXPERIMENTAL CONDITIONS.

3.1 TEST SPECIMENS.

The experiment was conducted on forty-three small specimens and two large panels, all with simulated lap splices. Each of the small panels contains 20 inspection sites. The large panels each contain 102 inspection sites. Thus, 1064 rivets were examined. Flaws were introduced into the sites as described in the following paragraphs.

The small specimens measure twenty by twenty inches. They contain two sheets of 0.040-inch-thick 2024 T-3 clad aluminum. Flaws were grown in the top sheet before the sheets were joined as a lap splice. The flaws were grown by fatigue cycling aluminum plates with undersize holes and starter cuts at the desired locations. All signs of the starter cuts were removed when the specimens were drilled to dimensions for joining as lap splices. See figure 1.

The large panels are eight and one half feet long and approximately four feet wide. These panels contain a single lap splice joint with all the frame structure behind the skins that would be in place in a typical Boeing narrow-body aircraft such as the 727 or 737. The flaws in these panels were grown through fatigue cycling. This was done on a special test bed that simulated the fuselage bi-axial pressure induced stress typically encountered in one flight cycle. Details about the test specimen structure can be found in references 1 and 2.

The surfaces of all the small specimens and one of the two large panels were painted with a typical aircraft paint. The surface of the second large panel was bare aluminum. A thin transparent 0.003-inch-thick tape was covering the inspection sites on the small specimens. This tape had been used in prior experiments (reference 2) to protect the test specimen surface from being scratched by probes and thereby providing visual clues to subsequent inspectors. However, small air bubbles beneath the tape were found to be affecting the inspections with the Nortec-30. The inspection probe on the Nortec-30 did not make surface contact with the specimen during the rotation of the sensors. Therefore, the tape was removed when it was determined that no adverse marring of the test specimen surface would occur.

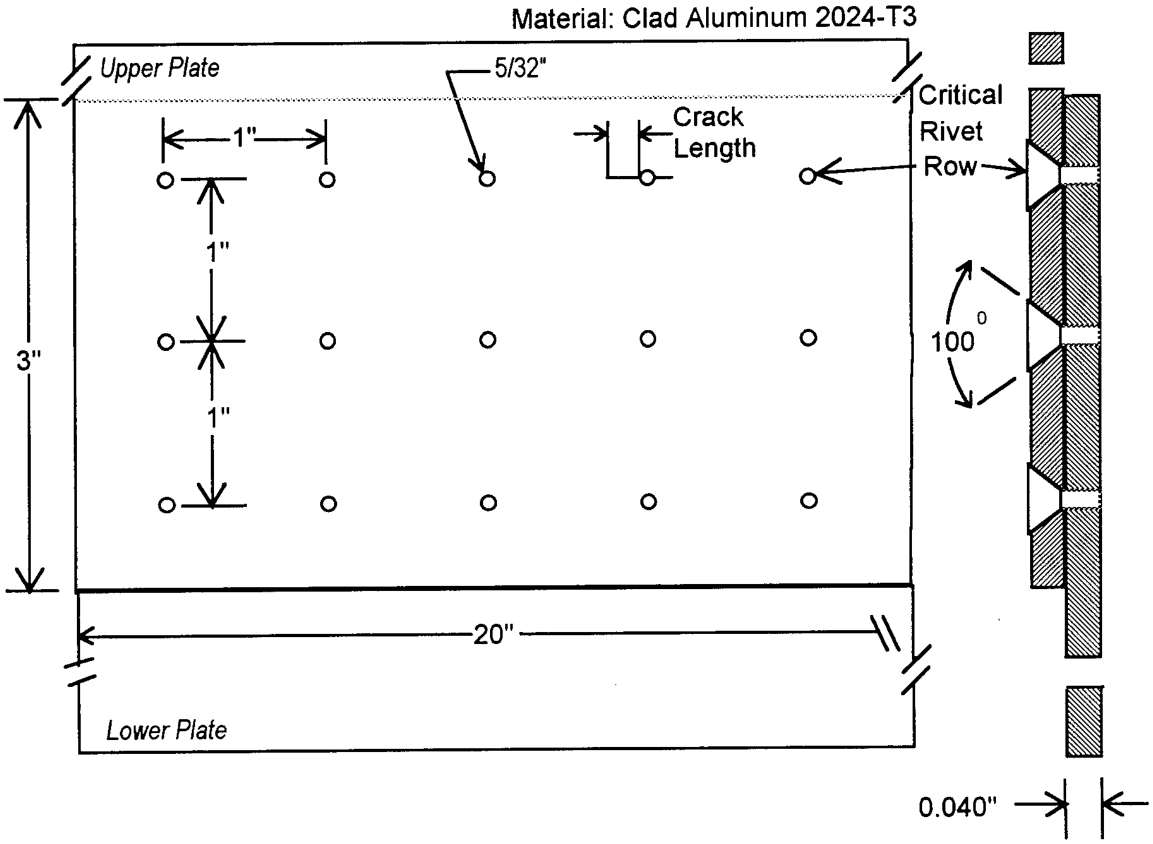

FIGURE 1. *SCHEMATIC OF SMALL SPECIMENS*

3.2 INSPECTION EQUIPMENT SETUP.

The inspections using the Nortec-30 were performed by the Eddy Current Product Manager from Staveley Instruments, Inc. The inspector set up the equipment using a Boeing Reference Standard #369 [3] supplied by the AANC. The Boeing #369 Standard contains an electro-discharge machined (EDM) notch that extends 0.100 inch from the edge of the countersink. The initial setup was checked against a standard in the possession of the inspector. This second standard had a 0.060-inch flaw. The setup was modified slightly to enhance the indication for this smaller flaw.

The resulting setup parameters were:

Gain	28.5 dB
Gate start	100 ms
Gate width	30 ms
Alarm level	not used
Rotation	354 °

For all inspections, the inspector was asked to use a 3-point subjective rating scale. A rating of 3 would mean that the inspector is certain that there is a reportable flaw indication. A rating of 2 indicates a reasonable certainty that a call of a flaw being present is correct. A rating of 1 is used to indicate the perception of a signal, but some doubt about the indication actually being reportable. For this inspection, the rating of 1 was applied to those signals that the inspector used such descriptions as, "There seems to be a signal, although at the current sensitivity level it would probably be passed by."

The inspector gave locations for all flaw indications. A monitor was present during the inspection and recorded the calls as they were made. The inspection of the 860 sites (20 × 43) on the small panels was done in a laboratory on a table top with the equipment operating on standard 110 AC wall current. The inspection of the 204 sites (102 × 2) on the large panels was done in the hangar with the Nortec-30 operating from batteries. The large panels were hanging vertically, simulating the fuselage of an aircraft.

4. INSPECTION RESULTS.

The 43 small panels were inspected in a five-hour period that included approximately one and one half hours for lunch and other breaks. The large panels were inspected in fifty minutes. The individual site (rivet) inspections, in general, took between 6 and 20 seconds, with an overall average of approximately 14 seconds per inspection site.

4.1 RELATIVE OPERATING CHARACTERISTICS.

A summary of the results of the inspection is given in table 1. In table 1, flaws are grouped into three categories which correspond to being under the rivet head (<0.05 inch), out from the rivet edge but less than the Boeing setup standard (0.05 to 0.10 inch), and larger than the Boeing setup standard (>0.010 inch).

Figure 2 presents the data of table 1 in the form of empirical relative operating characteristic curves. The points of the curves are the proportion of detects in each of the categories versus the false call rate. The first point of each curve is based on the strictest of criterion levels, that is the rating of 3. The second point shows how the detection rate varies when the criterion for making a call is relaxed, as is reflected by considering the 3 and 2 ratings. The third point reflects the most lenient criteria by incorporating the ratings of 1 into the detection level. The fourth point at (1,1) is the point that corresponds to calling every point a flaw. All ROC curves go through the point (1,1).

TABLE 1. *SUMMARY OF INSPECTION RESULTS*

		Ratings			
	No Call	1	2	3	Totals
*Nonflawed sites	688	13	4	3	708
< 0.050 inch flaws	25	11	5	6	47
0.050 to 0.100 inch flaws	3	0	4	86	93
> 0.100 inch flaws	0	0	0	144	144

*small specimens only

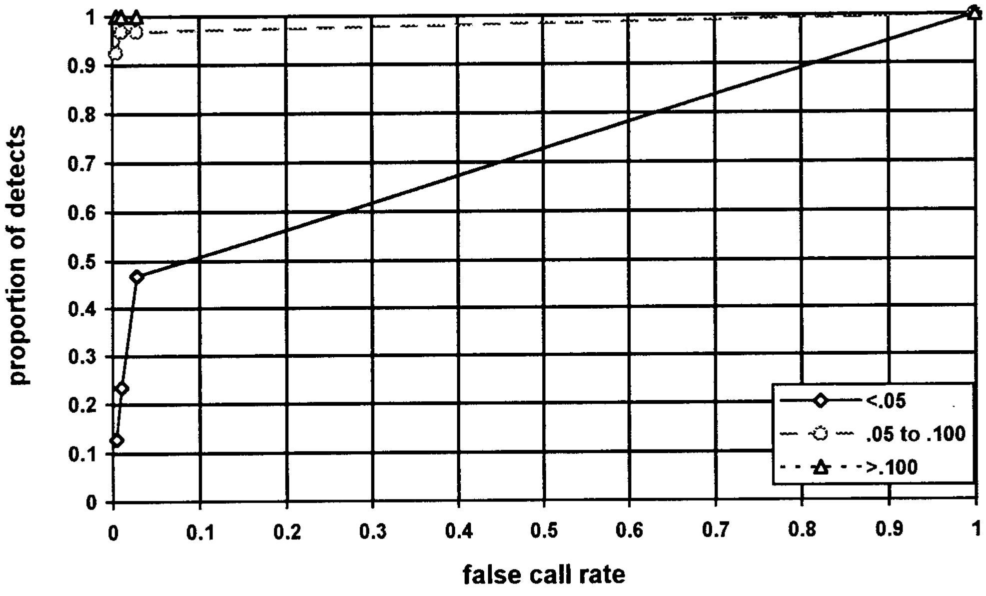

FIGURE 2. *EMPIRICAL RELATIVE OPERATING CHARACTERISTIC CURVE*

4.2 PROBABILITY OF DETECTION CURVES.

For the purposes of quantifying the probability of detection, curves are fit to the results (detect or miss) of the inspection for the known flaws. Four different mathematical fits are given for the data in figures 3 through 5. Figure 3 presents the curves fit to the "sure" calls (3's). Figure 4 presents the fitted curves for the detects with ratings of 3 or 2. Similarly, in figure 5 those curves fitting the most lenient criterion used (1's, 2's, and 3's) are given. False call rates (FCR) are given as the percentage of unflawed rivets where calls were made.

The curves that were fit to the data, as a function of the natural logarithm of the crack length, *a*, are:

$$(1/\sqrt{2\pi})\int_{-\infty}^{\alpha+\beta\cdot\ln(a)}\exp(-z^2/2)dz \qquad \text{Normal}$$

$$\frac{1}{1+\exp[-\{\alpha+\beta\cdot\ln(a)\}]} \qquad \text{Logistic}$$

$$1-\exp[-\exp\{\alpha+\beta\ln(a)\}] \qquad \text{Gompertz(1)}$$

$$\exp[-\exp\{\alpha+\beta\ln(a)\}] \qquad \text{Gompertz(0).}$$

The parameters, α and β, were estimated using maximum likelihood methods applied to binary response data as implemented by the SAS® procedure Probit [4]. The regression type models for binary data can be applied to the occurrence of either event, detect or miss. The symmetry of the Normal distribution guarantees that the fitted curve for the probability of detection is independent of whether one fits a curve to the detects or fits a curve to the probability of misses and then takes the complement. The parameters, α and β, will differ in sign, but will have the same magnitude. The same is true for the Logistic distribution. The Gompertz distribution, however, does not have that symmetry. The result of fitting the Gompertz distribution to the probability of detection is denoted Gompertz(1). The result of fitting the same distribution to the probability of nondetection and taking the complement is denoted as Gompertz(0).

There is no inherent reason why one curve should be adopted over another. The different forms are given here to illustrate variations present from the choice of representation. The Logistic and the Normal curves are very similar and are the most prevalent in use. The Normal curves for the three different Nortec 30 criterion levels are repeated in figure 6. They are compared with similar curve fits to laboratory inspection data gathered using sliding probe and template procedures [2]. The backgrounds on the reference 2 inspections are given in table 2.

All curves presented to this point have been best fit (maximum likelihood) curves. In figure 7, lower 95% confidence curves are given for the probabilities of detection for selected curves. All the fits in figure 7 are for the Normal form of the distribution. The curves not shown have similar shifts in the lower confidence curve compared to the curve of best fit.

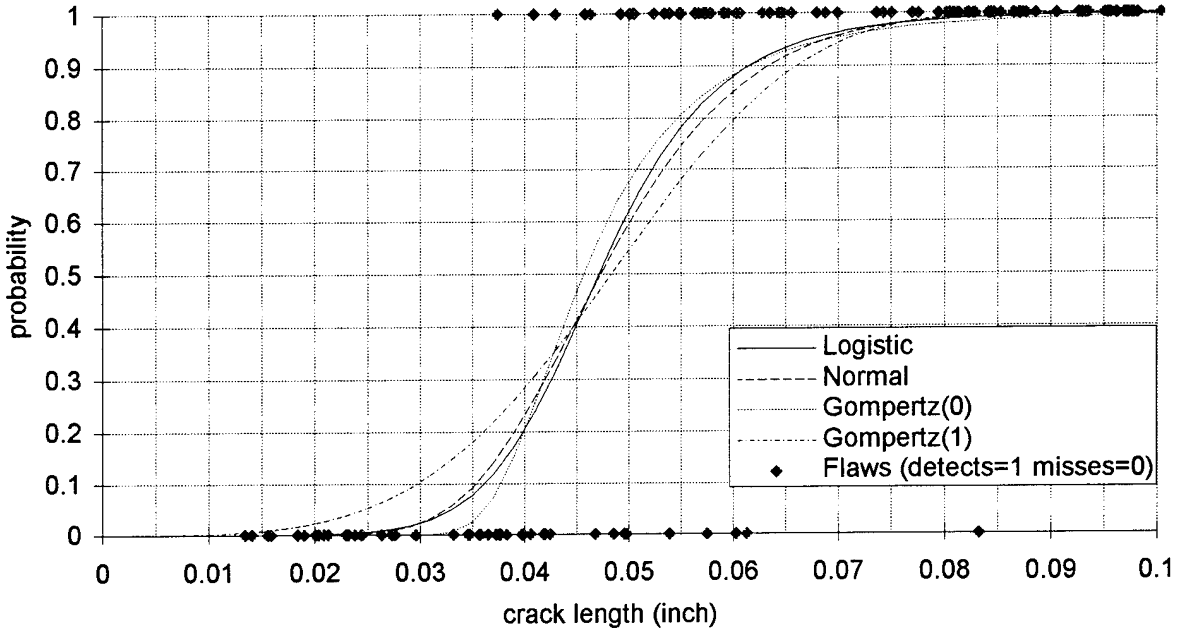

FIGURE 3. *PROBABILITY OF DETECTION CURVES FOR MOST STRINGENT CRITERIA (false call rate at 0.4 percent).*

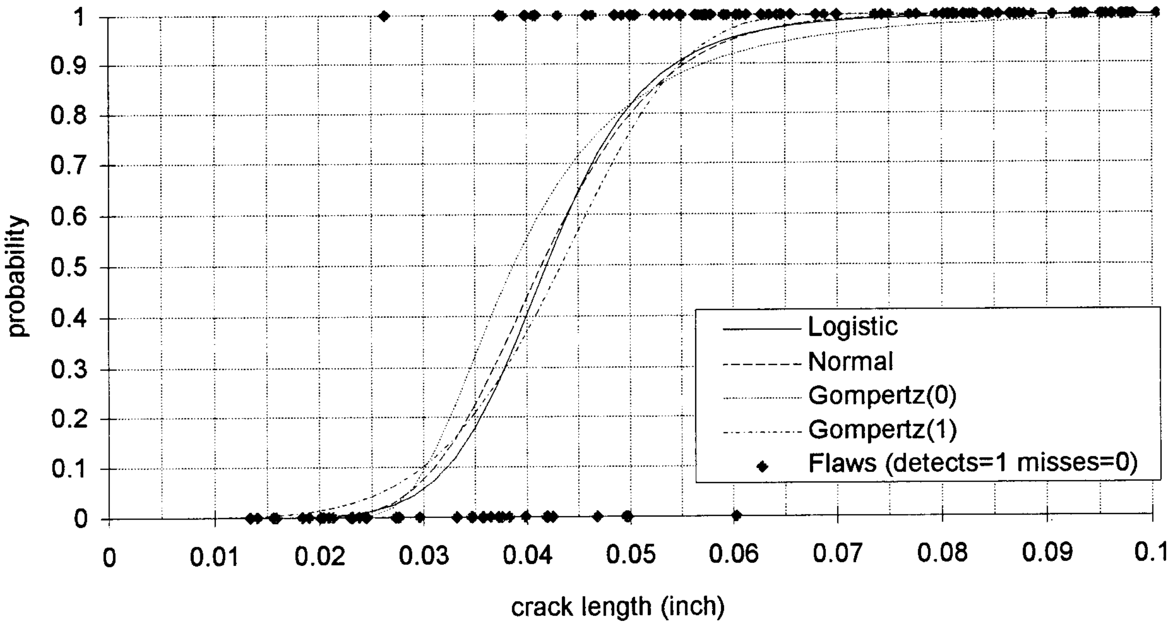

FIGURE 4. *PROBABILITY OF DETECTION CURVES FOR LESS STRINGENT CRITERIA (false call rate at 1.0 percent).*

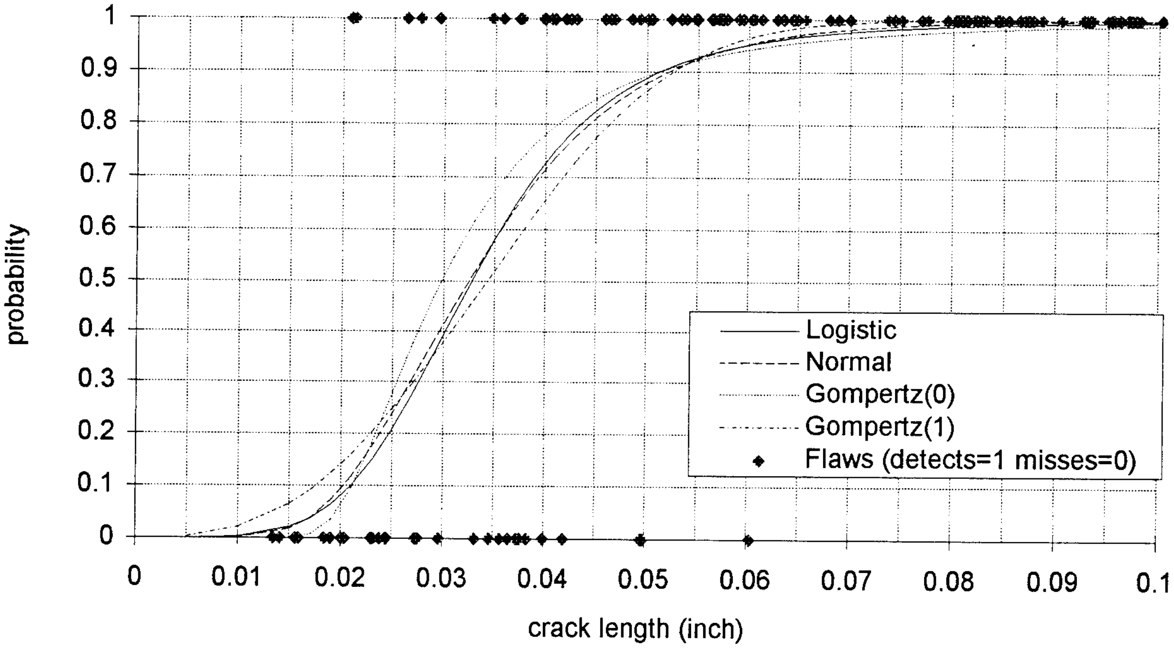

FIGURE 5. *PROBABILITY OF DETECTION CURVES FOR RELAXED CRITERIA (false call rate at 2.8 percent).*

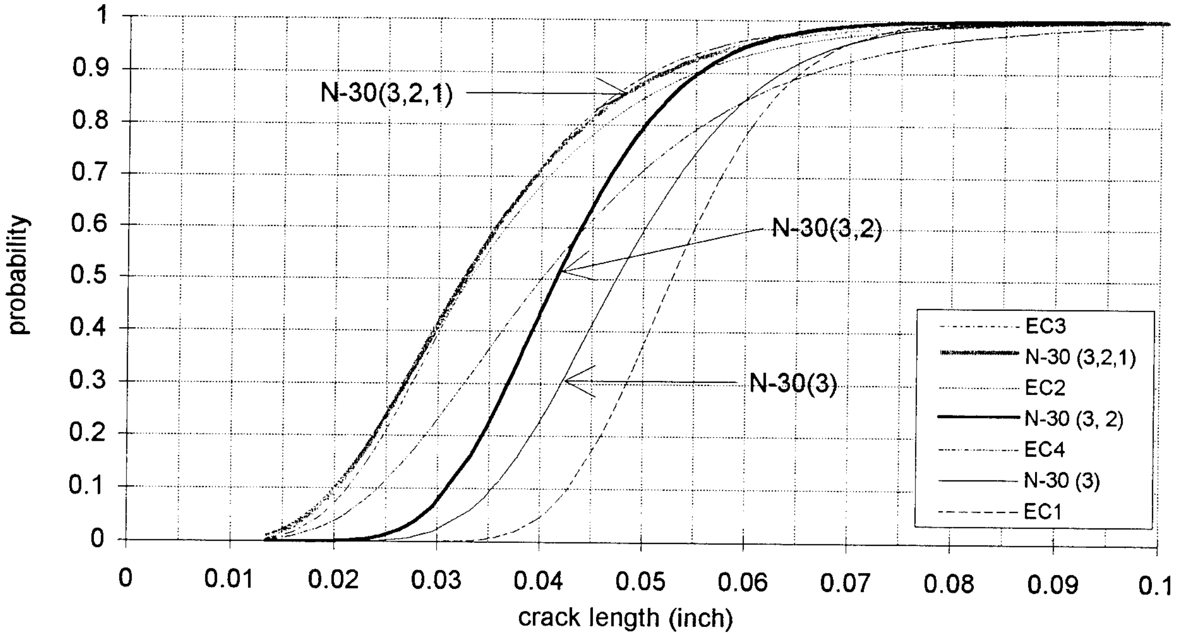

FIGURE 6. *NORTEC-30 COMPARED TO OTHER EDDY CURRENT INSPECTIONS Legend order is from largest to smallest probability at 0.05 inch.. All curves are Normal fits.*

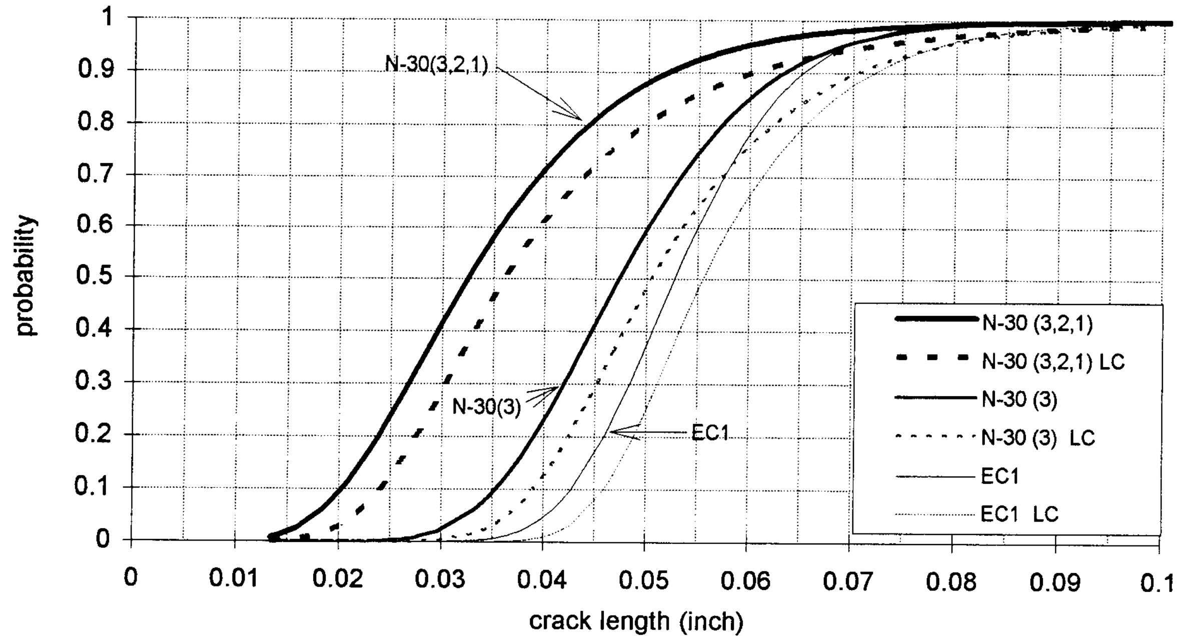

FIGURE 7. *LOWER 95 PERCENT CONFIDENCE CURVES FOR NORMAL POD FITS. Similar shifts occur for cases not shown.*

TABLE 2. *BACKGROUND ON REFERENCE 2 LABORATORY INSPECTIONS. All used a Rohmann Elotest B2 Eddy-Current Instrument.*

Inspection	Qualifications	Procedure	False Call Rate (%)
EC1	NDT Level III, Supervisor and Examiner - >25-years aircraft experience	Sliding probe - 16 kHz	0.9
EC2	NDT Level III, ASNT Level III - >25 years in NDT training	Template - 20 kHz	0.3
EC3	ASNT Level III - >18 years in NDT training and development	Template - 30 kHz	0.3
EC4	ASNT Level II - 13-years experience in NDT inspection and development	Template - 30 kHz	0.9

5. SUMMARY AND DISCUSSION.

The reported inspection results represent a single inspector using the Nortec-30 Eddyscan. The inspector was an Eddy Current Product Manager from Staveley Instruments, Inc. and was well versed with the use of the instrument.

The inspector gave subjective ratings to the various calls. The relatively steep receiver operating curve (figure 2) for the class of flaws less than 0.050 inch in length indicates the presence of signal above background noises. Half of the flaws detected in this category were rated as 1. In these cases the inspector expressed the opinion that a signal was likely present but that the initial setup (on 0.100-inch flaw) was not sensitive enough to give a clear indication.

All flaws greater than 0.100 inch in length were detected. The largest flaw missed, smallest flaw detected, 0.90 probability fit, and flaw size for which the lower 95% confidence interval on probability of detection exceeds 0.9 for each criteria level are given in table 3. The latter two values are estimated using the Normal distribution function.

TABLE 3. *SUMMARY FLAW LENGTHS.*

Criterion Level	Largest flaw missed (inch)	Smallest Flaw detected (inch)	Flaw length for 0.90 PoD -- Normal fit	Flaw length for which lower 95% conf. int. for PoD is > 0.9
Stringent (3's, FCR=0.4%)	.083	.037	.063	.070
Moderate (3,2's, FCR=1.0%)	.060	.026	.055	.062
Lenient (3,2,1's, FCR=2.8%)	.060	.021	.052	.060

Using the most stringent criterion, the Nortec-30 inspection achieved better probability of detection than was achieved using a sliding probe. At the moderate criterion level, the false call rates for the Nortec-30 are comparable to that obtained with the sliding probe (EC1 of figure 6) but with an approximate shift in probability of detection curves of 0.01 inch.

With the most lenient criterion level, the Nortec-30 probability of detection curve is almost identical with that fit to the highly qualified inspectors using template and pencil probe (EC2 and EC3 of figure 6). However, the false call rate was almost 3% as compared to 0.3% with the template procedures.

The ability of the Nortec-30 Eddyscan system to use the "off-center" signal to give direct feedback on centering the probe was a time-saver. No appreciable time differences were observed in inspecting the painted large panel versus the unpainted large panel. However, the lighting conditions under which the inspections were done would have forced more time to be spent on the painted panel in visually locating and centering rivets within a template had a pencil probe been used. The inspections of 204 rivet sites on panels that simulated an aircraft fuselage took 53 minutes to complete.

All the Nortec-30 inspection results are from a single inspector performing inspections over a large number of test specimens. This enables probability of detection curves to be fitted to each inspector-equipment combination. Inspector-to-inspector variations exist as is evidenced in comparing EC3 and EC4 results. The information on the Nortec -30 Eddyscan System presented here should be taken as reflective of capabilities when used by a well-trained inspector using setup procedures similar to those currently employed in field inspections.

6. REFERENCES.

1. Spencer, Borgonovi, Roach, Schurman, and Smith, "Reliability Assessment at Airline Inspection Facilities, Vol II.: Protocol for an Eddy Current Inspection Reliability Experiment," DOT/FAA/CT-92/12, II, May 93.

2. Spencer, Floyd and Schurman, Don, "Reliability Assessment at Airline Inspection Facilities, Vol III.: Results of an Eddy Current Inspection Reliability Experiment" DOT/FAA/CT-92/12, III, May 95.

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