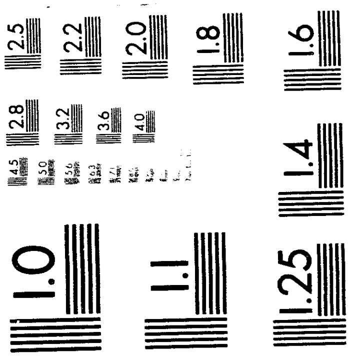

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Inspection Reliability of a Nortec-30 Eddyscan System*

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Abstract

This report presents the results of an inspection around fastener holes in simulated lap splice specimens using a Nortec-30 Eddyscan inspection system. The inspector performing the tests had no prior knowledge of the extent or location of cracks in the specimens examined. The results of the inspection are presented in terms of various probability of detection curve models and are compared to various other eddy current inspections performed on the same set of test specimens. Results indicate that the system is capable, with high confidence, of detecting 60 to 70 mil cracks from under countersink fasteners.

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Introduction

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.

1. 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.

2. Experimental Conditions

<u>Test Specimens</u>

The experiment was conducted on forty-three (43) small specimens and two (2) 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. (Details are given in reference [1].)

The small specimens measure twenty inches by twenty inches. They contain two sheets of .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 (8 ½) feet long and approximately four (4) 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 Reference 1.

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. The experiment was started with a thin transparent 3 mil tape over the inspection sites on the small specimens. This tape had been used to protect the 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. 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, as it was slowing the inspection and it was determined that no adverse marring of the surface would occur.

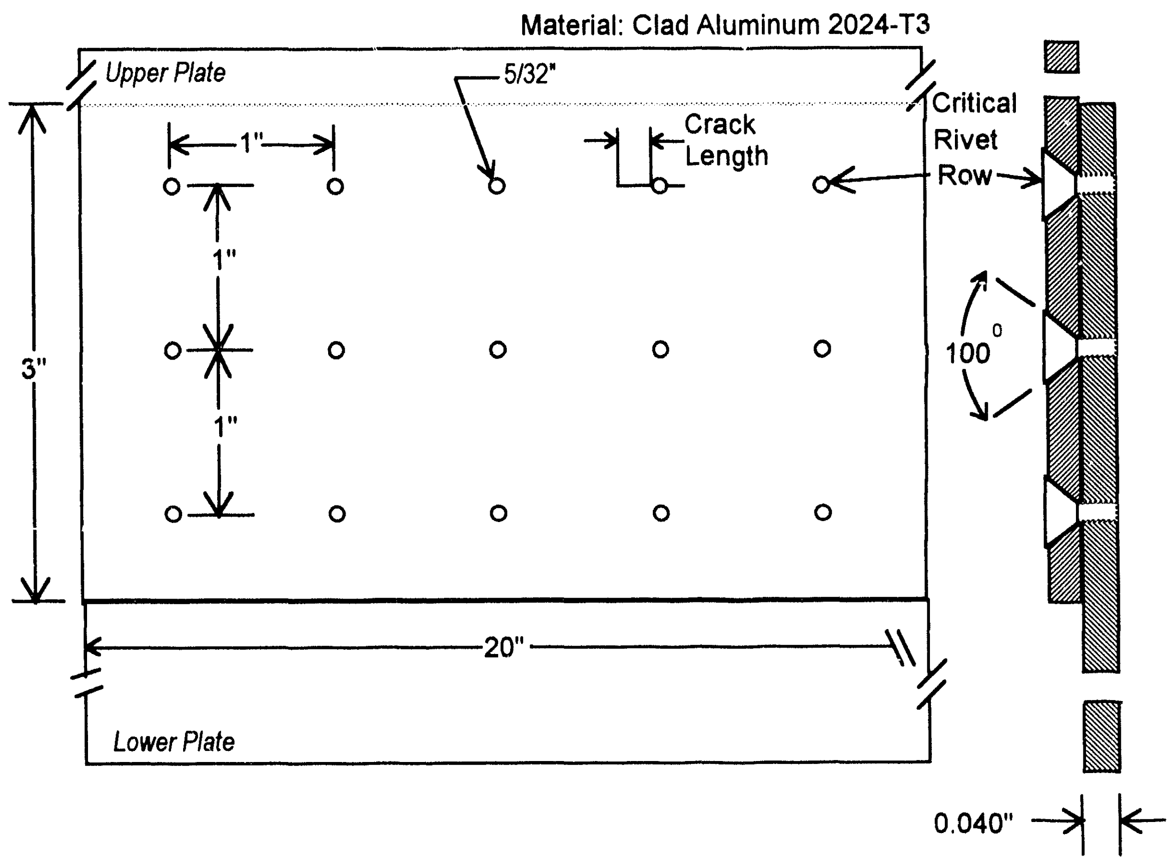

Figure 1 *Schematic of small specimens*

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 supplied by the AANC. The Boeing #369 standard contains an EDM notch that extends 0.100 inches 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 being made. The inspection of the 820 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.

3. Inspection Results

The 43 small panels were inspected in a five (5) hour period that included approximately one and one half (1½) hours for lunch and other breaks. The large panels were inspected in fifty (50) 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.

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 (<50 mils), out from the rivet edge but less than the setup standard (50 to 100 mils), and larger than the setup standard (>100 mils).

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 "3s." The second point shows how the detection rate varies when the criterion for making a call is relaxed, as is reflected by considering the "3s" and the "2s." The third point reflects the most lenient criteria by incorporating the "1s" into the detection level.

Table 1. *Summary of Inspection Results*

	No Call	"1s"	"2s"	"3s"	Totals
*Non-flawed 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

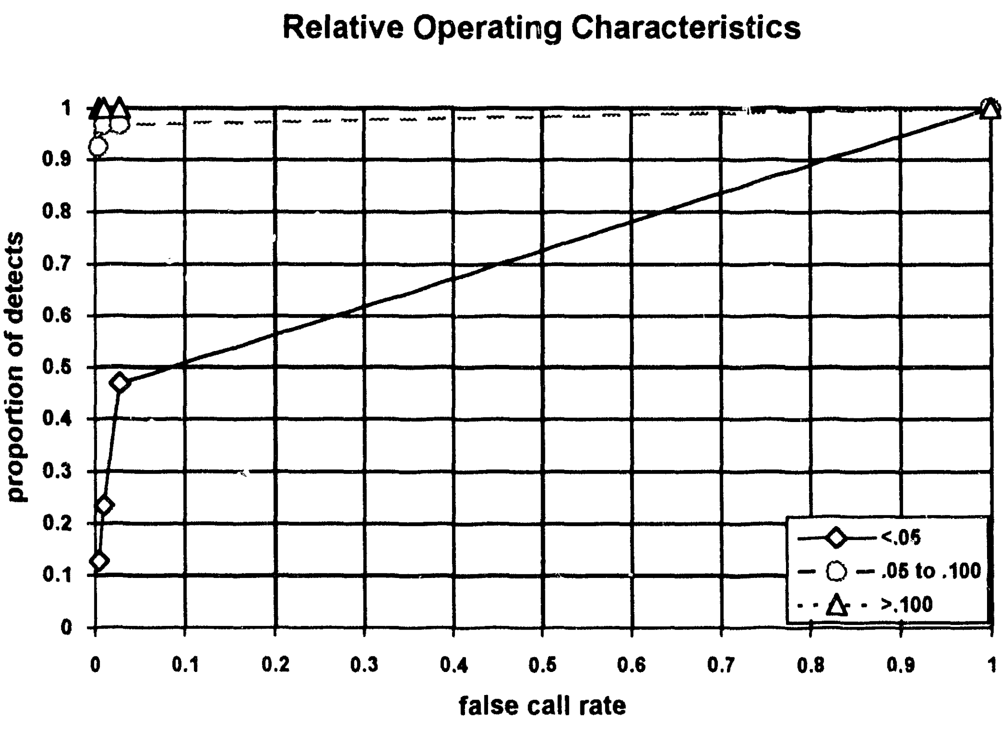

Figure 2. *Empirical Relative Operating Characteristic Curve*

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:

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

$$1/(1+\exp(-\{\alpha + \beta \ln(a)\})) \qquad \text{(Logistic)}$$

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

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

The parameters, α and β, were estimated using maximum likelihood methods applied to binary response data as implemented by the SAS® procedure Probit. 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 {1 – exp(-exp(x)}to the probability of detection is denoted Gompertz(1). The result of fitting the same distribution to the probability of non-detection 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 variation 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 3 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 those 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.

Probability of Detection Curves - Nortec 30
(3 Calls - FCR= .4%)

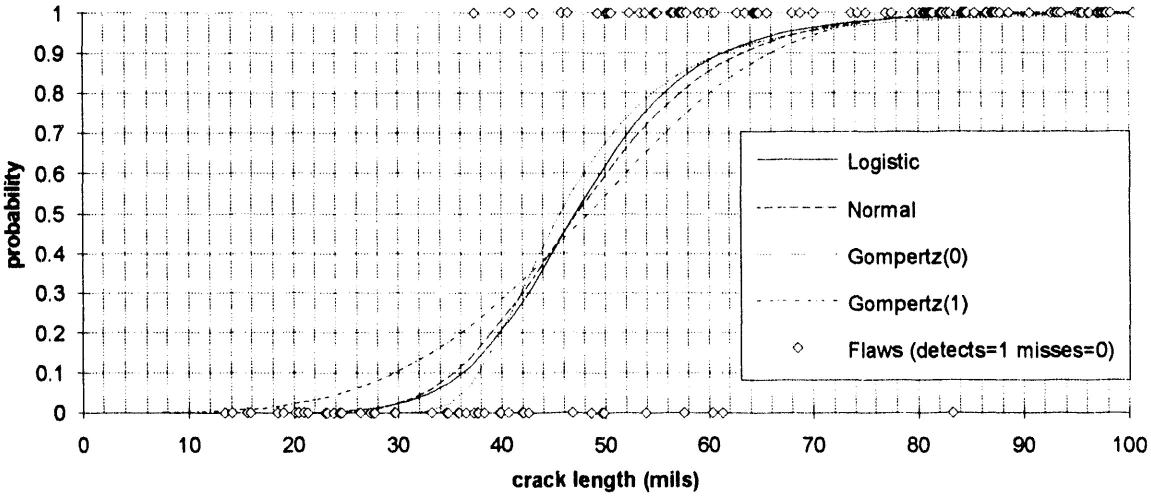

Figure 3. *Probability of Detection curves for most stringent criteria (false call rate at .4%).*

Probability of Detection Curves - Nortec 30
(3,2 Calls - FCR= 1.0%)

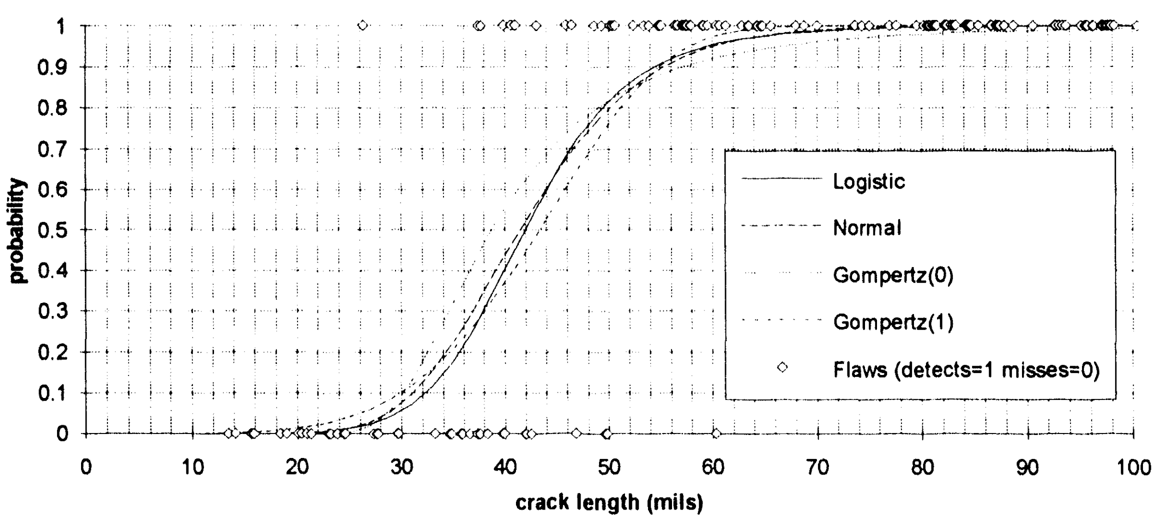

Figure 4. *Probability of Detection curves for less stringent criteria (false call rate at 1.0%).*

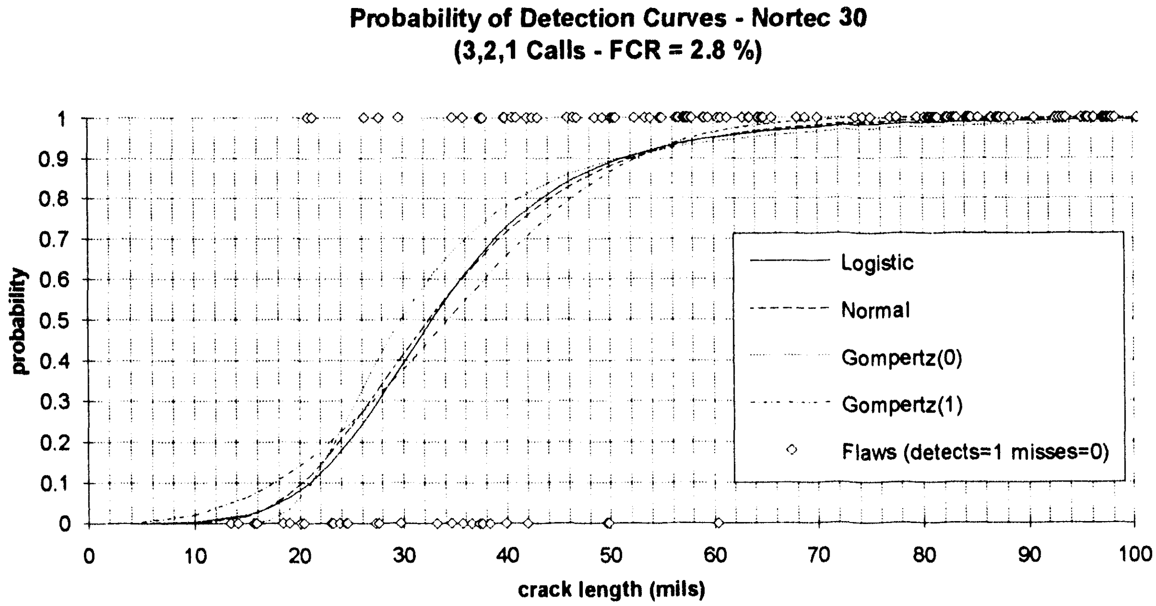

Figure 5. *Probability of Detection curves for relaxed criteria (false call rate at 2.8%).*

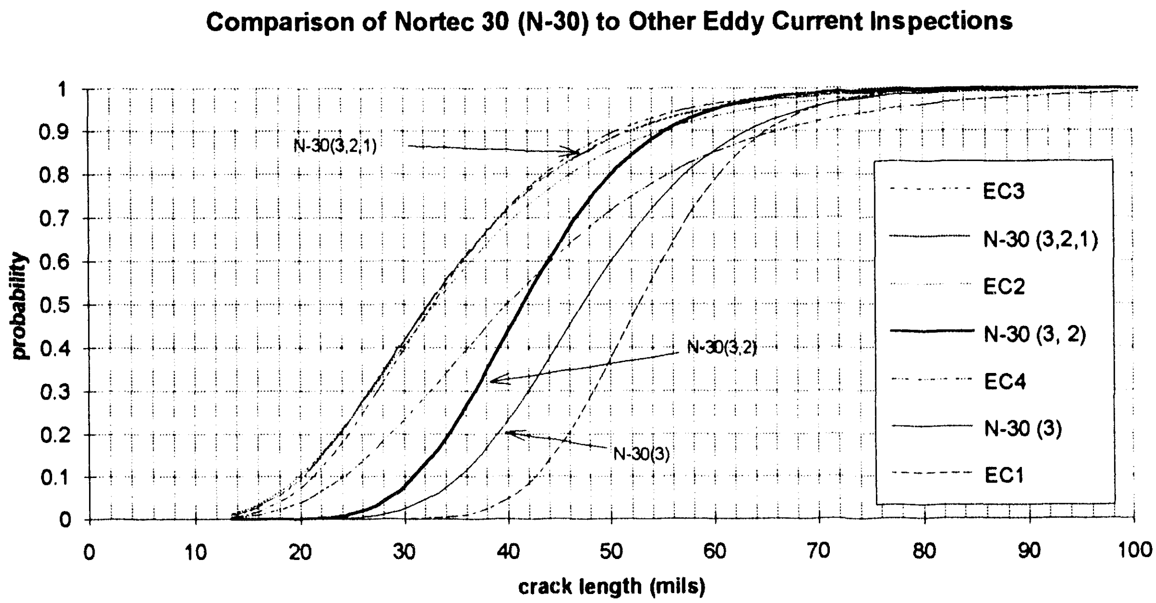

Figure 6. *Nortec 30 compared to other eddy current inspections Legend order is from largest to smallest probability at 50 mils. All curves are Normal fits.*

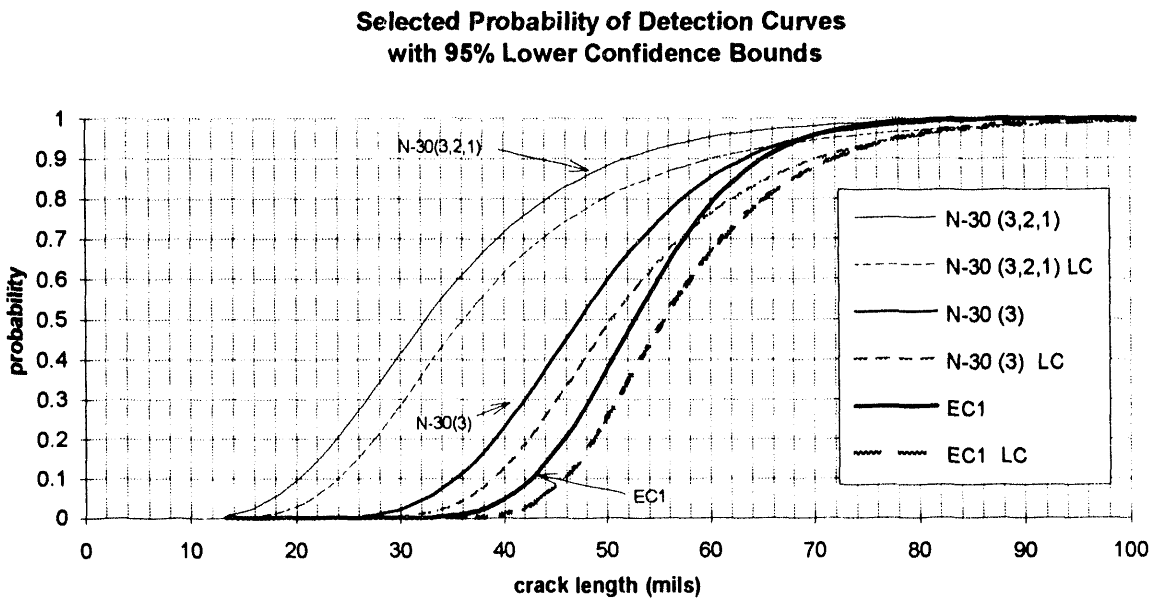

Figure 7. *Lower 95% Confidence Curves for Selected Normal PoD fits. Similar shifts occur for cases not shown.*

Table 2. *Background on Reference 2 Laboratory Inspections. All used Rohmann Elotest B2.*

Inspection	Qualifications	Procedure	False Call Rate (%)
EC1	NDT Level III, Supervisor and Examiner - >25 years aircraft experience	Sliding probe - 16 kHz	.9
EC2	NDT Level III, ASNT Level III - >25 years in NDT training	Template - 20 kHz	.3
EC3	ASNT Level III - >18 years in NDT training and development	Template - 30 kHz	.3
EC4	ASNT Level II - 13 years experience in NDT inspection and development	Template - 30 kHz	.9

4. 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 relative steep relative operating characteristic curve (Figure 2) for the class of flaws less than 0.050 inches in length indicates the presence of signal above background noise. Half of the flaws detected in this category were rated as "1s." In these cases the inspector expressed the opinion that a signal was likely present but that the initial setup (on a 0.100 inch flaw) was not sensitive enough to give a clear indication.

All flaws greater than 0.100 inches in length were detected. The largest flaw missed, smallest flaw detected, .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 the following table. The latter two values are estimated using the Normal distribution function.

Criterion Level	Largest flaw missed (mils)	Smallest Flaw detected (mils)	Flaw length for .90 pod -- Normal fit	Flaw length for which lower 95% conf. int. for pod is > .9
Stringent (3's, FCR=.4%)	83	37	63	70
Moderate (3,2's, FCR=1.0%)	60	26	55	62
Lenient (3,2,1's, FCR=2.8%)	60	21	52	60

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 but with an approximate shift in probability of detection curves of 10 mils (compare EC1 of Figure 6.)

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% achieved 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 in visually locating and centering the rivets on the painted panel had a template and pencil probe been used. The inspections of 204 rivet sites on panels that simulated an aircraft fuselage took 53 minutes to complete.

All results and comparisons reported are from single inspectors 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.

Reference

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.

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.(to be published spring '94)

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