THE ROLE OF PHYSICAL MODELING OF INSPECTION PROCESSES

R. B. THOMPSON

CENTER FOR NDE
AEROSPACE ENGINEERING & ENGINEERING MECHANICS
MATERIALS SCIENCE & ENGINEERING
IOWA STATE UNIVERSITY
AMES, IOWA 50011

INTRODUCTION

ASSUMPTIONS

Physical modeling involves two types of assumptions

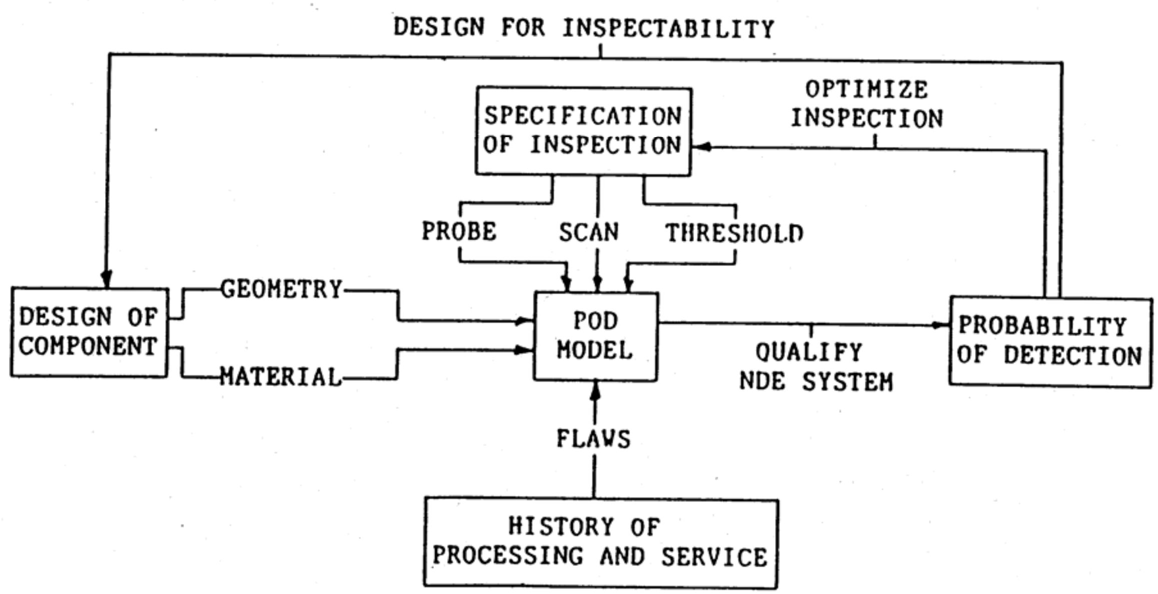
> **That the geometry modeled corresponds to the geometry of interest. (e.g. that the assumed flaw has the same shape as the natural flaw)**

> **That the governing differential equations and boundary conditions have been satisfied with sufficient accuracy**

In this paper, we will <u>not</u> address these issues and, instead, will examine the way that models can be utilized, assuming sufficient accuracy.

However, it should be emphasized that careful attention to the above matters is needed, including validation experiments on well-controlled geometries. An important part of a modeling program is establishing ranges of validity.

ROLE OF PHYSICAL MODELING THROUGHOUT LIFETIME OF A COMPONENT



T. A. Gray, R. B. Thompson, B. P. Newberry: Review of Progress in QNDE 6A, p. 957 (1987)

I. OPTIMIZATION OF INSPECTION PARAMETERS

PIONEERING WORK IN ENGLAND

Journal of Nondestructive Evaluation, Vol. 9, No. 2/3, 1990

A System Model for the Ultrasonic Inspection of Smooth Planar Cracks

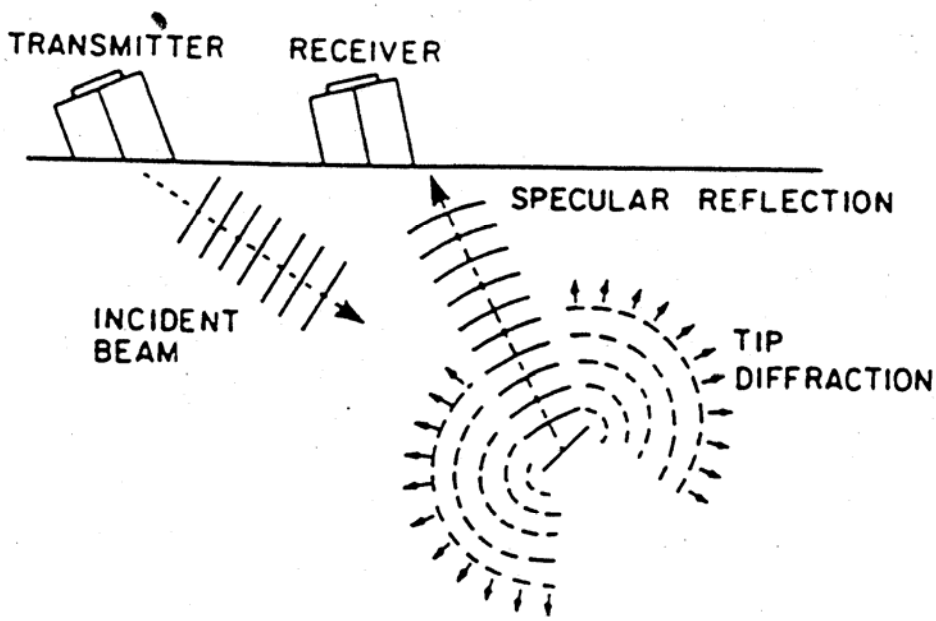
R. K. Chapman[1]

Received March 13, 1990; revised June 19, 1990

This paper describes a system model for the ultrasonic inspection of smooth planar cracks in ferritic steel, using pulse-echo probes. The model predicts the echo amplitudes and ranges as functions of the probe position. It is applied to problems of procedure design, assessment, and technical justification on power station plant. The model is implemented as a suite of versatile and user-friendly computer codes, suitable for use by practical NDT engineers, and is supported by a comprehensive user manual. The paper describes the principles of the model and gives examples of its application to power plant problems. Illustrations are also given of the extensive validation which the model has undergone through comparison with experiment.

KEY WORDS: Ultrasonic inspections; theoretical modeling; elastodynamic; geometrical theory of diffraction; Kirchhoff theory; probe; computer codes; experimental validation; defect detection; power station plant.

Models were developed by the Central Electricity Board as part of the technical case supporting the safety of the Sizewell B power plant in a recent Public Inquiry in England. For his contributions, Dr. Chapman was honored by the British Institute of NDT at their 30th annual meeting (1991).



- The models included two types of wave scattering phenomena. Specular (mirror-like) reflection was modeled by the Kirchhoff approximation and tip diffraction by the Geometrical Theory of Diffraction (GTD).

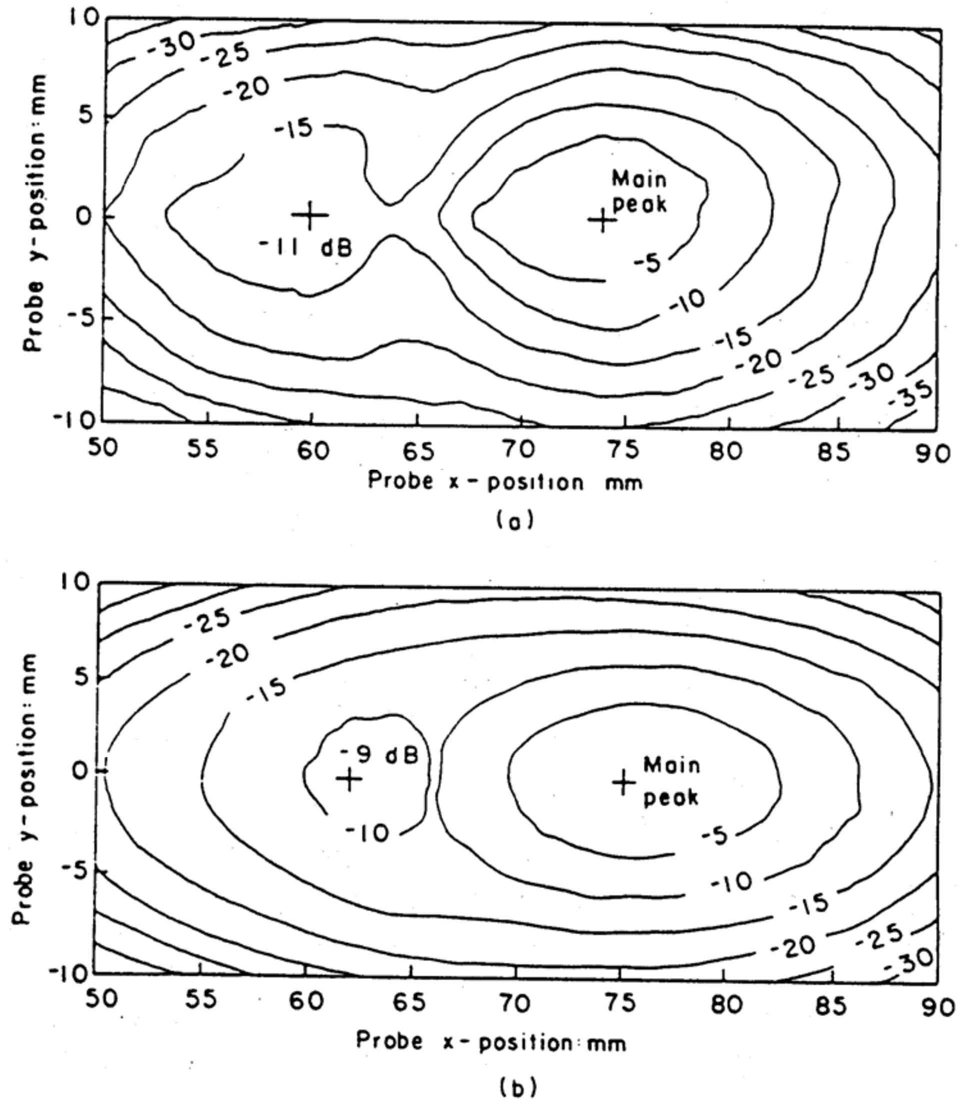


FIGURE 17. Comparison of Kirchhoff theory and experiment for scattering from simulated pressure vessel flaws. The case considered is C-scan plots of the response of a 55°, 2 1/2 MHz pulse-echo shear wave probe to a 10 mm diameter flat-bottomed hole at a depth of 46 mm and tilted at 30° to the vertical. (From Coffey, J. M. and Chapman, R. K., *Nucl. Energy*, 22, 319, 1983.)

- The Kirchhoff theory was validated against experiment.

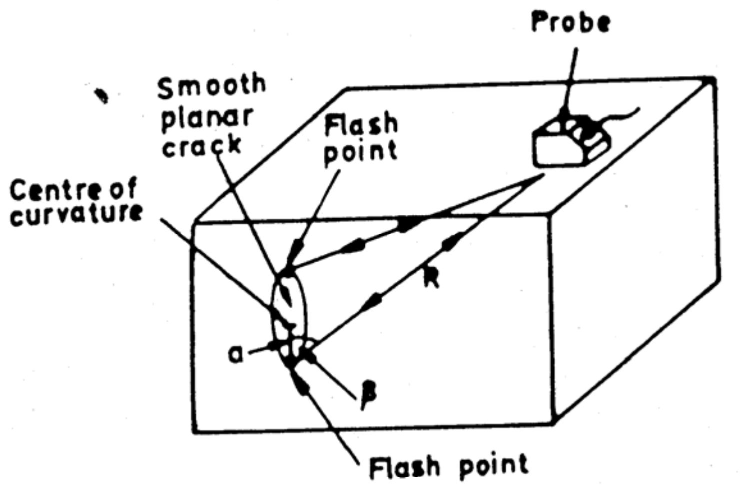


Fig. 5. Detection of top and bottom edge waves in pulse-echo inspection.

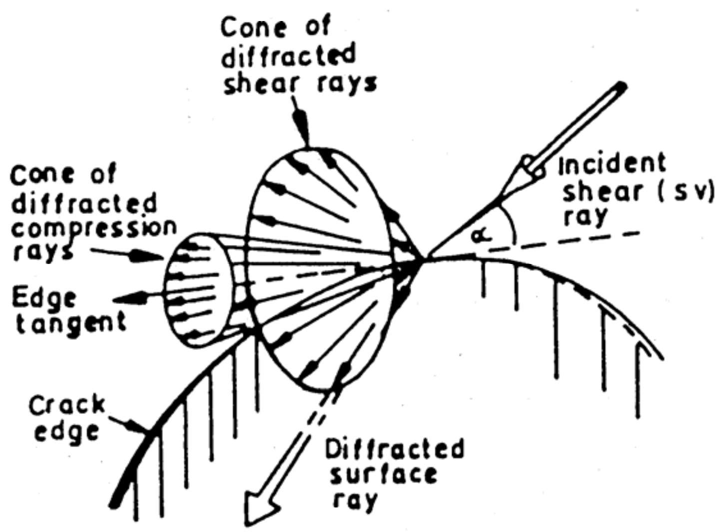


Fig. 4. Diffraction of a shear ray by a curved crack edge.

- These sketches provide some of the technical details involved in applying GTD. The top sketch defines the "flash point", which are the points on the crack edge which contribute to the observed signal. The bottom sketch shows that the diffracted signals take the form of cones of energy emanating from the crack edge.

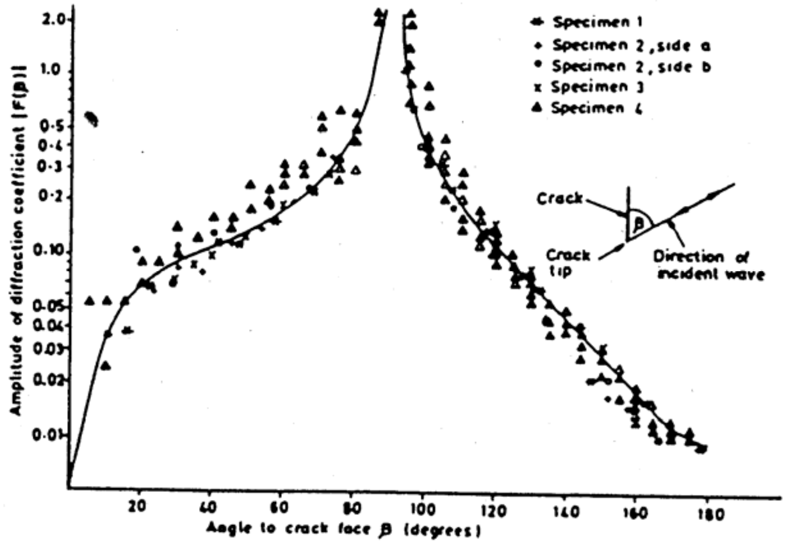


Fig. 6. Diffraction coefficient for back-scatter of compression waves from smooth planar crack: comparison between theory (solid line) and experiment (marked points). Results for specimens 1–3 from Burch *et al.*[18] and results for specimen 4 from Toft.[17]

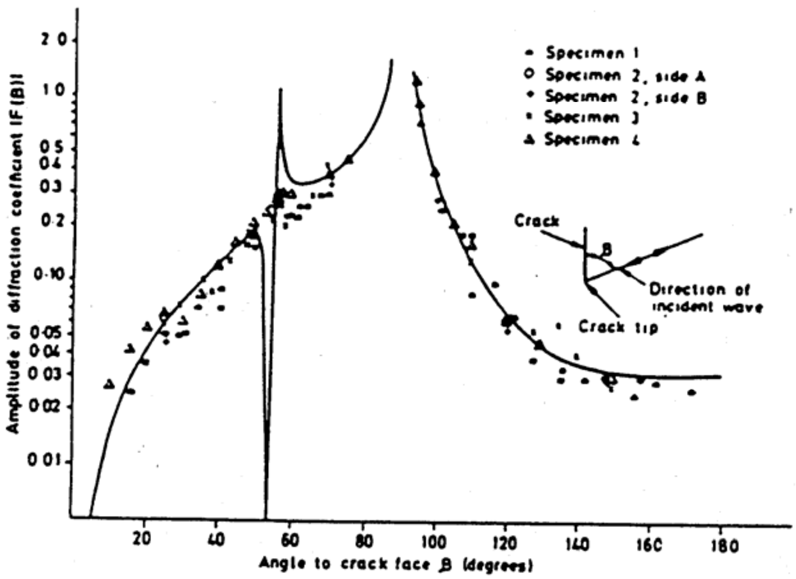


Fig. 7. Diffraction coefficient for back-scatter of shear (SV) waves from smooth planar crack: comparison between theory (solid line) and experiment (marked poinits). Results for specimens 1–3 from Burch *et al.*[18] and Burch and Tattersall,[19] and results for Specimen 4 from Toft[17]

- The diffracted signals strengths are proportional to diffraction coefficients, whose values have been validated experimentally.

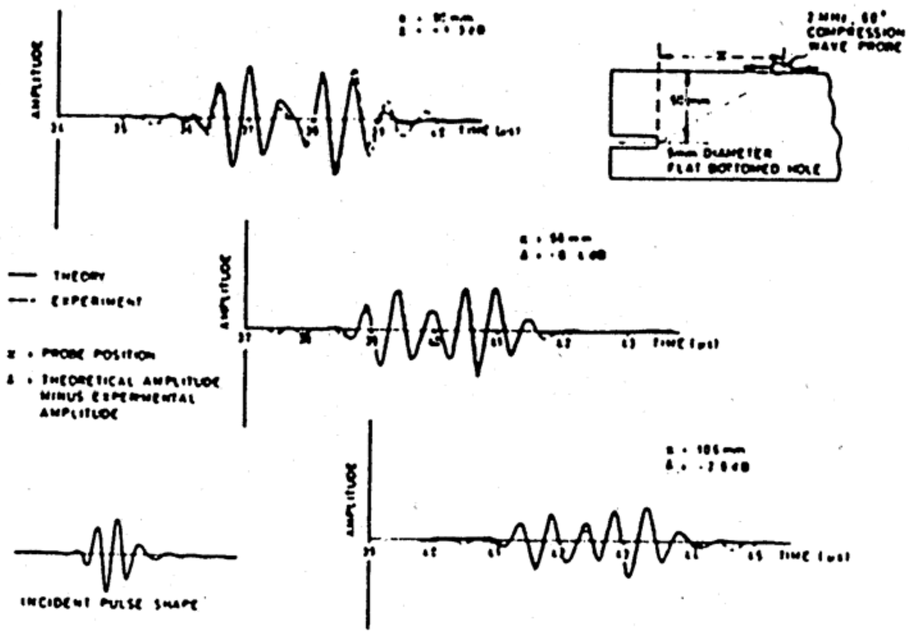


Fig. 13. Comparison between GTD code and experiment for inspection of 9-mm diameter flat-bottomed hole by 2-MHz, 60° compression wave probe.

- Here a detailed, time-domain validation of the GTD mode is shown.

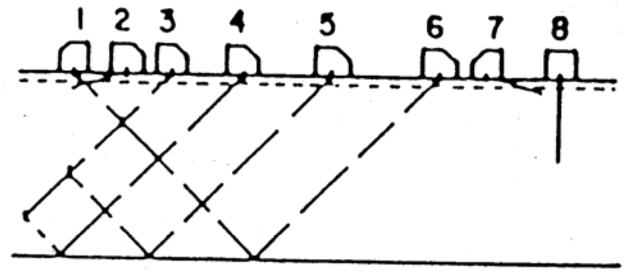


Fig. 19. Multiple probe arrangement for the inspection of pressure vessels. Beam paths are shown by dashed lines. Note redundant paths and the use of different pairs to detect specular reflectors at different depths (after [91]).

- These codes have been used to design inspection configurations for the Sizewell B pressure vessel based on a "worst case". A set of probes are sought which will produce an acceptable signal level from flaws believed to be most difficult to detect.

II. QUALIFICATION OF A SYSTEM

Nondestructive Evaluation

Ultrasonic Testing: Computer Modeling Applications

by Michael J. Avioli, Jr., Nuclear Power Division

ABSTRACT *Under Appendix VIII of ASME Section XI, the qualifications of ultrasonic testing personnel who conduct in-service inspections at nuclear power plants must be established through performance demonstrations. To help utilities meet this requirement, EPRI is exploring the use of computer modeling in the design of qualification samples, the optimization of inspection procedures, and the extension of samples and procedures to a broader range of cases. Such modeling applications promise to improve inspection reliability and reduce the costs of qualification.*

- In the U.S., considerable interest has recently arisen in modeling. In the nuclear power industry, this is driven by the desire to extend the life of power plants.

ASME BOILER AND PRESSURE VESSEL CODE

SECTION XI
RULES FOR INSERVICE INSPECTION

APPENDIX VII
QUALIFICATION OF NONDESTRUCTIVE EVALUATION PERSONNEL FOR ULTRASONIC EXAMINATION
(1988)

APPENDIX VIII
PERFORMANCE DEMONSTRATION FOR ULTRASONIC EXAMINATION SYSTEMS
(1989)

- One important motivator is the requirements of Appendix VIII, Section XI of the ASME Boiler and Pressure Vessel Code.

ESSENTIAL VARIABLE TOLERANCES (ARTICLE VIII-4000)

The qualified procedure may be modified to substitute or replace pulsers, receivers, or search units without requalification when the following conditions are met.

Pulser: pulse amplitude ± 10%
pulse rise time ± 10%
pulse duration ± 10%

Receiver: -6 dB points ± 0.2 MHz
center frequency ± 0.2 MHz

Search Units: propagation angle ± 3 deg
center frequency ± 20%
waveform duration, greater of ± 1/2 cycle or 20%
bandwidth ± 10%

SUPPLEMENT 5 - QUALIFICATION REQUIREMENTS FOR NOZZLE INSIDE RADIUS SECTI0N

Demonstration on clad/base metal interface of reactor vessel plate specimens (Supplement 4) qualifies examination procedures, equipment, and personnel for nozzle radius section examination when the following requirements are met.

a minimum of three additional flaws at the inside radius section in one or more full-scale nozzle mock-ups

for O. D. examination, at least one nozzle in the set shall be at least 90% of the maximum thickness

for O. D. examination, at least one nozzle in the set shall have the ratio of the nozzle thickness to shell thickness within + 30% of that ratio for the vesssel nozzles to be examined

- This states that a demonstration of capability is only valid when certain essential variables are held quite close to the values used in the demonstration and when the part geometry is quite close to that of the mock-up.

PERFORMANCE DEMONSTRATION INITIATIVE
(ad hoc utilities committee)

DRIVERS:

High cost of replicating plant components and implanting defects

Growing shortage of inspectors

Costs of conducting demonstrations

ACTION:

Computer modeling identified as a key element in improving inspection reliability

OBJECTIVES:

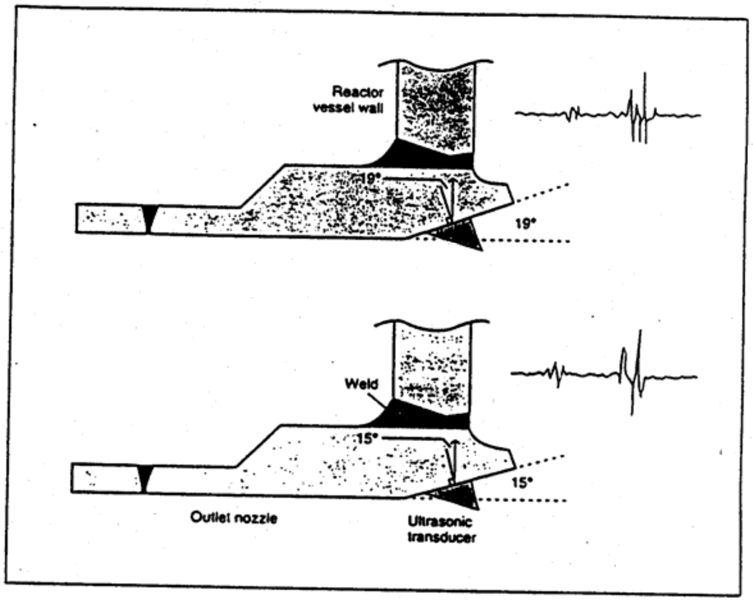
Extend the range of application of qualified procedures

Minimize the number of necessary samples and demonstrations

Optimize procedures

- The resulting costs (both in demonstration labor and mock-up construction) are quite high. Hence modeling is being considered as a cost savings tool.

EQUIVALENCE OF PROCEDURES



- One simple application is in demonstration the equivalence of procedures for which the essential variables have changed outside of their acceptable bounds.

MINIMIZATION OF THE NUMBER OF SAMPLES AND DEMONSTRATIONS REQUIRED

ULTRASONIC INSPECTION MODELING APPLIED TO SELECTION OF PERFORMANCE DEMONSTRATION TEST SPECIMENS FOR NOZZLE INNER-RADIUS INSPECTION

B J Dikstra and C McNeil
Babcock Energy Limited

F L Becker
EPRI NDE Center

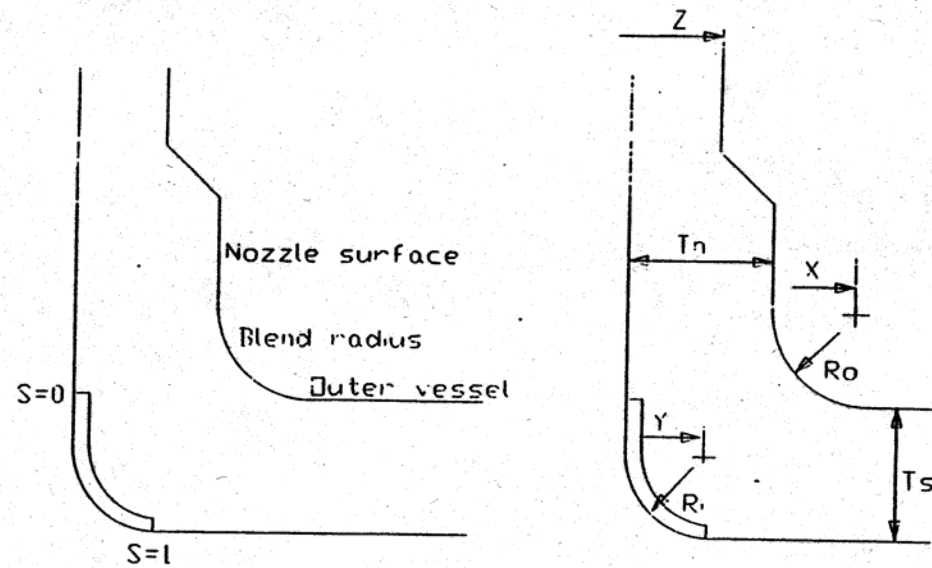
SUMMARY

Appendix VIII on Performance Demonstration of the ASME code Section XI requires full scale mock-ups for demonstrating ultrasonic examinations of the nozzle inside-radius region. For BWR plant the rules mean that at least six different specimens are needed to cover the full range of nozzles in operating plant. A study using a computer model of ultrasonic examination has been carried out to investigate how examination performance depends on nozzle geometry. Preliminary results suggest that it would be possible to divide nozzles into three categories on the basis of the types of scanning required. Hence the test specimen requirement might be reduced to three; one for each category. Recommendations for further work are made.

REFERENCE

EPRI Computer-Assisted Technologies for NDE & Plant Monitoring Workshop: August 10-13, 1992.

- Researchers from Babcock Energy have used models to minimize the number of performance demonstration test specimens which need to be constructed.



Examination volume and scan surfaces.

Parameters X,Y and Z are measured from the nozzle axis.

Figure 1. Nozzle Inside-Radius Examination Volume and Scan Surfaces.

- **Particular problem of interest; nozzle inside-radius examination**

VISIBILITY MAPS

RAY TRACING USED TO IDENTIFY POINTS OF TRANSDUCER POSITION

KIRCHHOFF APPROXIMATION USED TO ASSIGN AMPLITUDES TO NEAR SPECULAR SIGNALS DUE TO DIRECT REFLECTION OR CORNER TRAP REFLECTION

Compact flaw: 0.44 in.
1.5 MHz shear probe
0.8 in. crystal diameter
Visibility in % DAC for 7/16 inch side-drilled hole

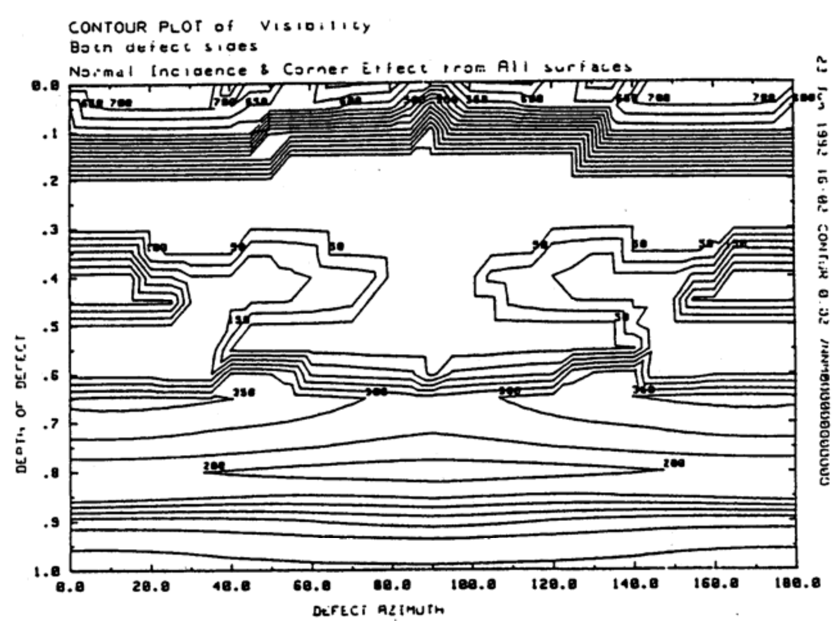
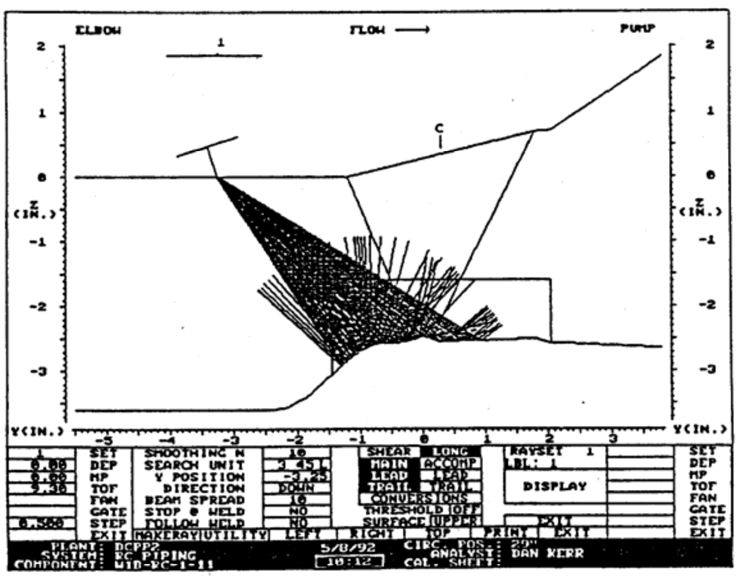


Figure 2. Visibility Map : Nozzle No 2 (Feedwater) - Direct Detection and Corner Effect - All Surfaces

- An output is a set of visibility maps giving the relative strength of the signals for different flaw positions. These have been used to group a wide variety of nozzle geometries into 3 categories, each with similar coverage during UT inspection.

ANALYSIS AND REFINEMENT OF PR0CEDURES (RAYTRACE)



- Other tools are in routine use by the electric utilities. Raytrace is a 2-D code which traces rays through complex geometries. While not quantitatively predicting waveforms, it provides useful feedback in inspection design and interpretation.

DEVELOPMENT OF SOFTWARE FOR IMPLEMENTATION ON UTILITY WORKSTATIONS.

3D VISUALIZATION FOR UT DETECTION AND SIZING

M. Koshy
J. Isenberg
L. Carcione

Weidlinger Associates
Los Altos, CA

REFERENCE

EPRI Computer-Assisted Technologies for NDE & Plant Montoring Workshop: August 10-13. 1992

- A second generation set of tools. including 3-D ray tracing and physical modeling of defect signals. is being developed by Weidlinger Associates, in collaboration with the Center for NDE at Iowa State University.

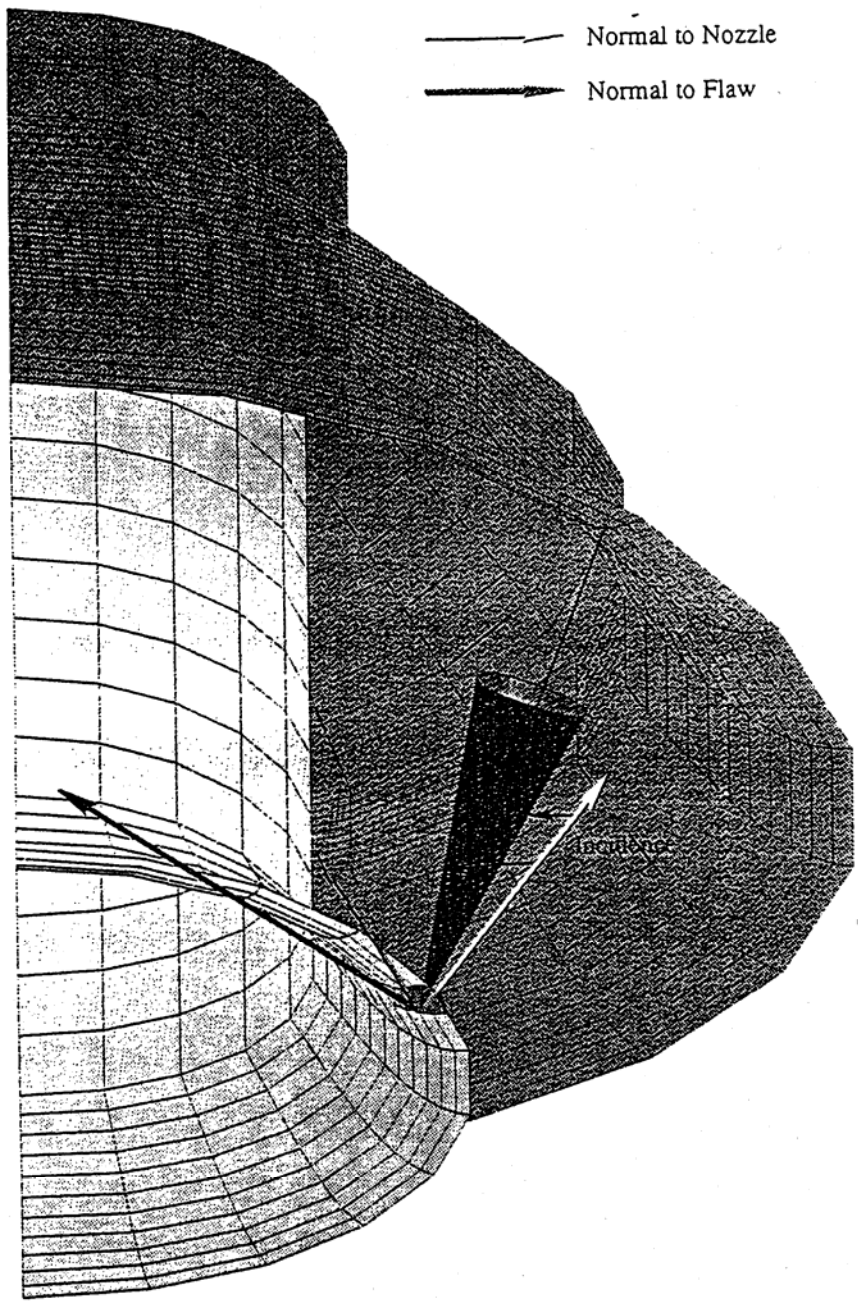


Figure 10. Incidence angle defined on inner surface of nozzle.

- This is an example of a 3-D model of a nozzle, showing the cone of incidence angles that would produce a corner trap signal of an acceptable amplitude.

III. APPLICATION TO AIRCRAFT ENGINE ROTATING COMPONENTS

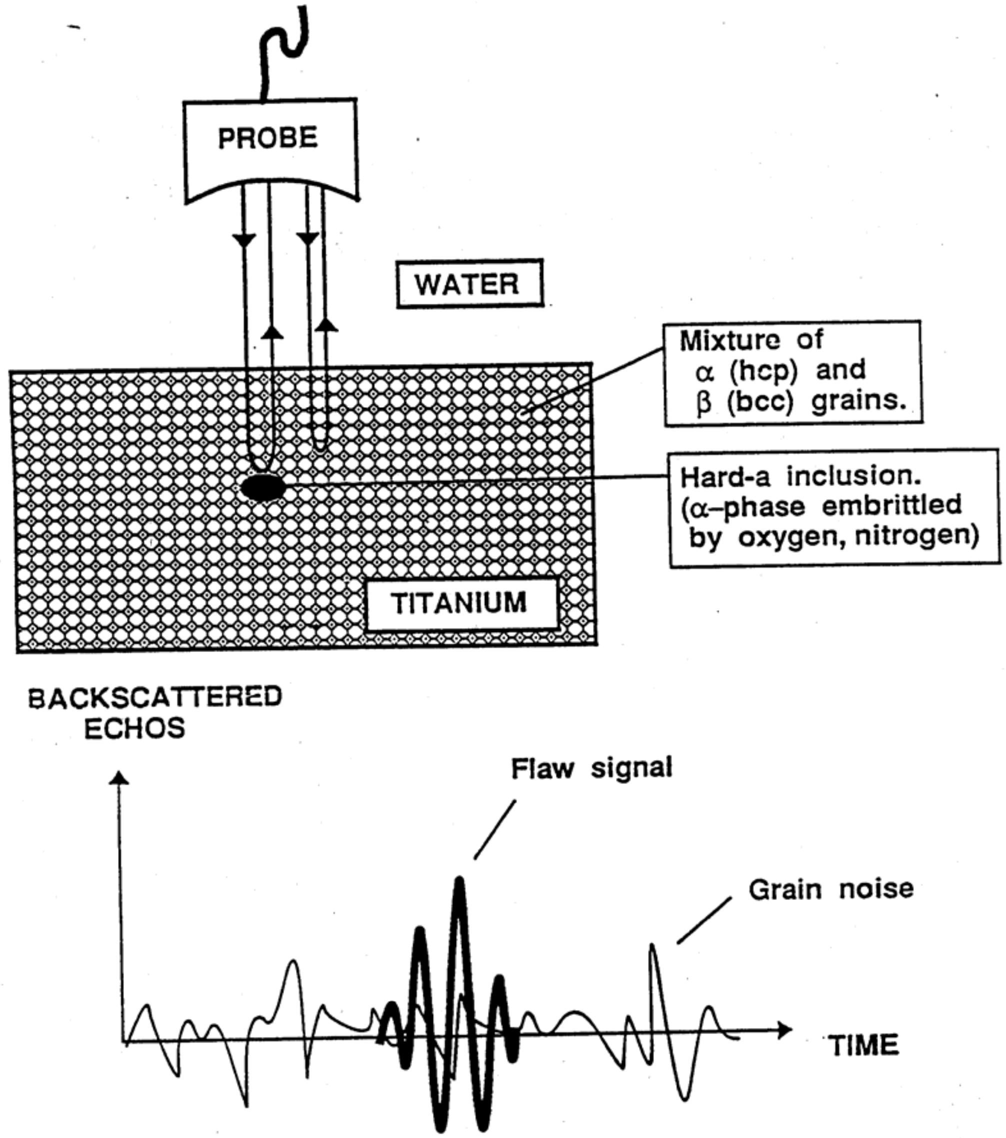
REFERENCES

R. B. Thompson, F. J. Margetan, H. K. Han, A. J. Paxson and C. E. Shamblen, "Relationship of Microstructure to Backscattered Ultrasonic Noise," Review of Progress in Quantitative Nondestructive Evaluation 11B, D. O. Thompson and D. E. Chimenti, Eds. (Plenum Press, NY, 1992) pp. 1685-1691.

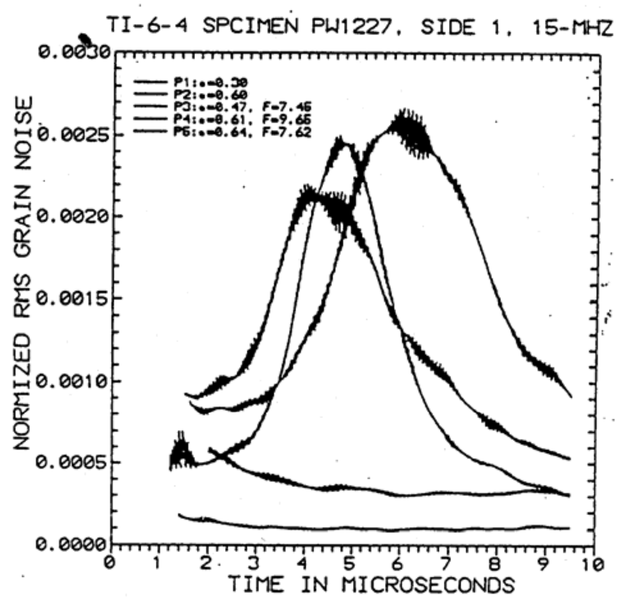
F. J. Margetan and R. B. Thompson, "Microstructural Noise in Titanium Alloys and its Influence on the Detectability of Hard-Alpha Inclusions," ibid, pp. 1717-1724.

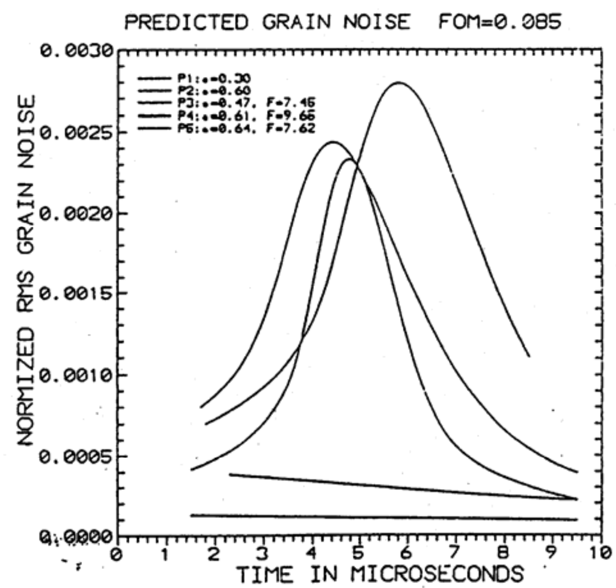
James H. Rose, "Ultrasonic Noise from Microstructure," ibid, pp. 1677-1684.

ULTRASONIC DETECTION OF HARD-α INCLUSIONS IN TITANIUM ALLOYS

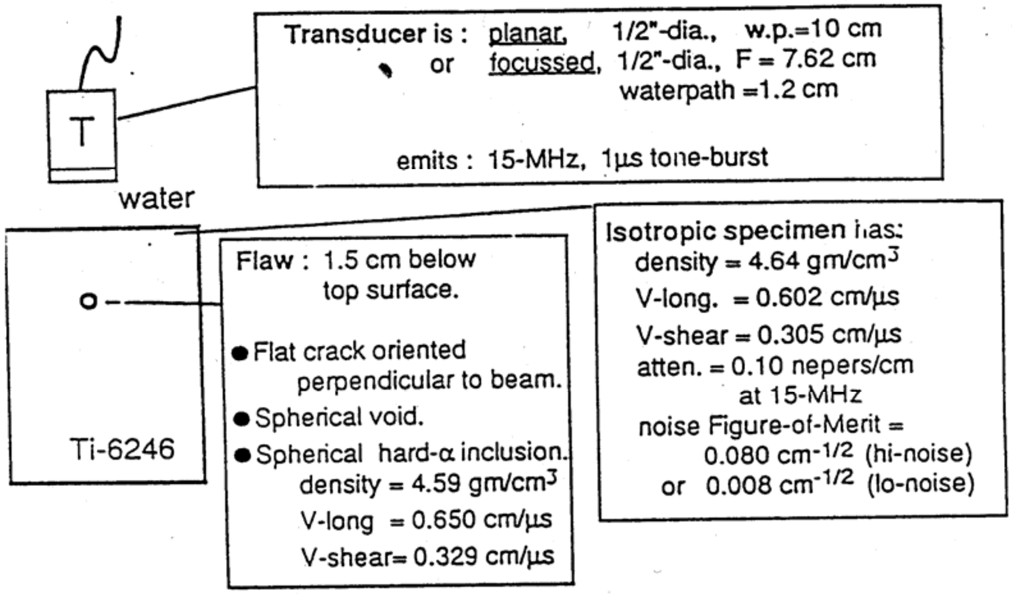


- Scientists at the Center for NDE at Iowa State University have recently developed models for the detectability of metallurgical defects, such as hard alpha inclusions, in aircraft engine components. These require models for the grain noise as well as the inclusion signals.





- **The noise model predictions (bottom) are compared to measurements (top) in these figures for 5 different probes (3 focussed, 2 unfocussed) at 15 MHz. On a T_i-6Al-4V sample, good agreement is obtained when the material is characterized by a noise figure-of-merit (FOM).**



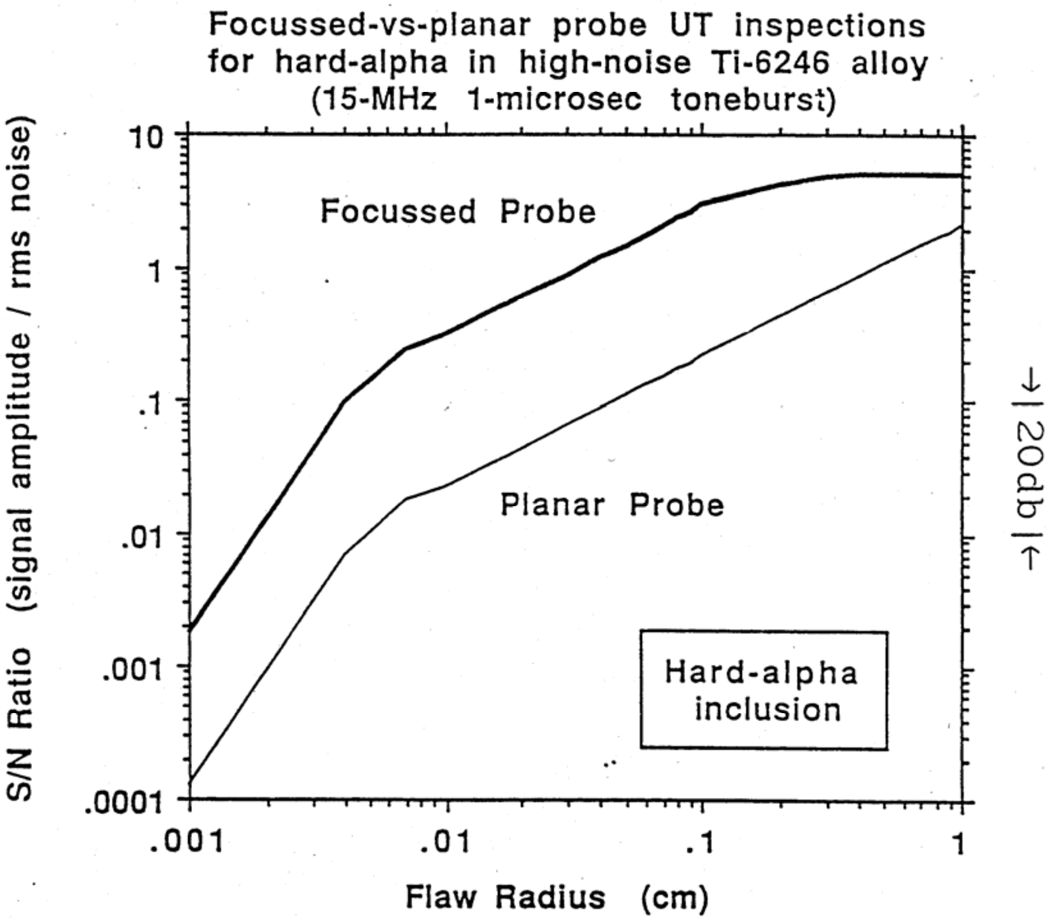
Procedure:

- Use noise model to calculate: $\frac{\text{rms-noise amplitude}}{\text{ref. signal amplitude}}$

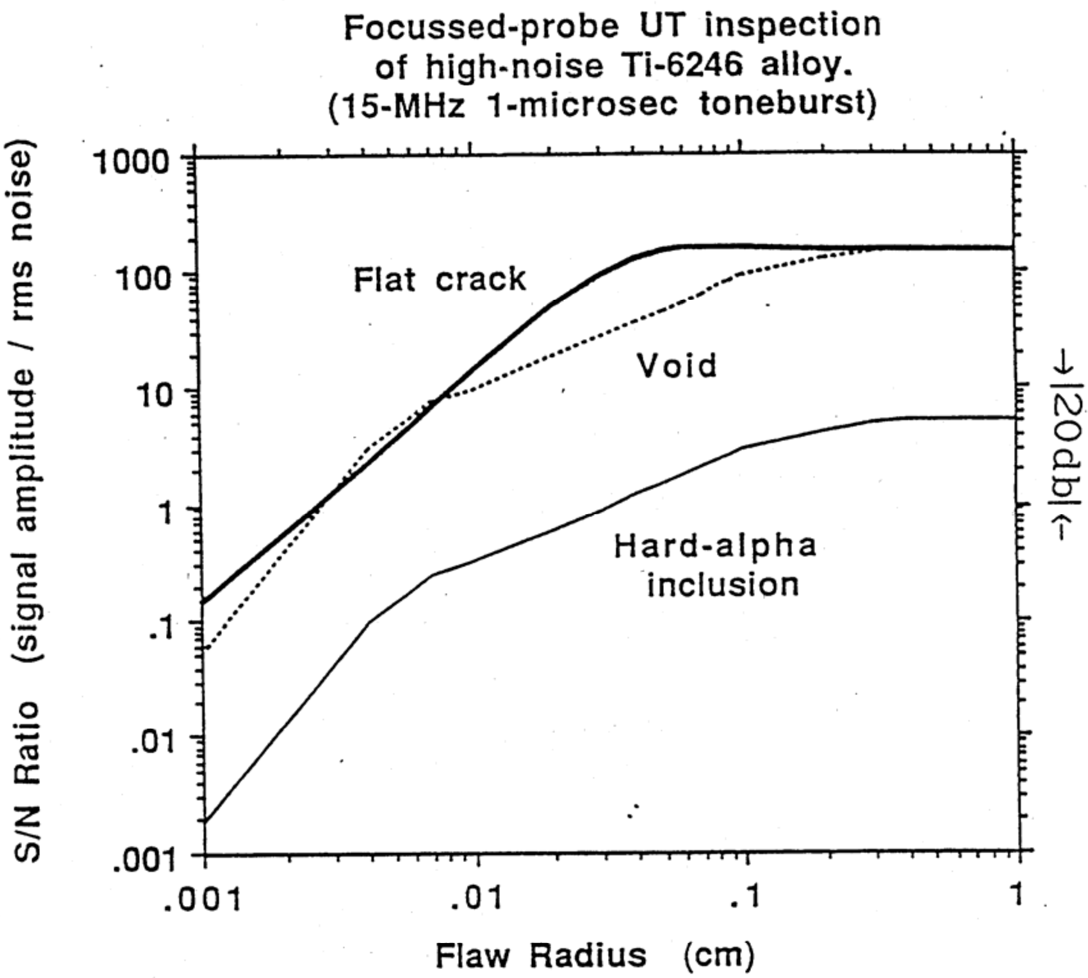
- Use Thompson/Gray measurement model to calculate: $\frac{\text{flaw signal amplitude}}{\text{ref. signal amplitude}}$

- Divide to get : $\frac{\text{flaw signal amplitude}}{\text{rms-noise amplitude}}$

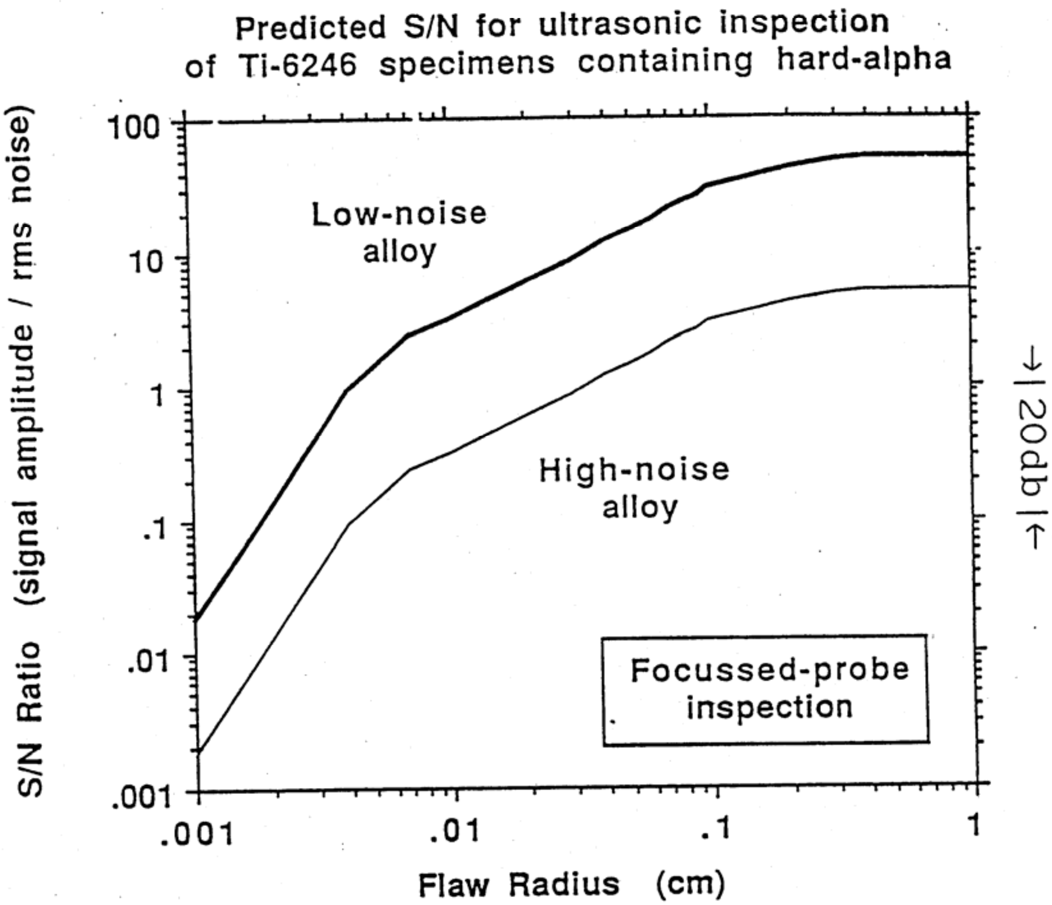
- **Such models can be used to predict signal-to-noise ratios for practical inspection scenarios. Here we consider the S/N ratio for three flaws types in a "noisy" and a "quiet" alloy.**



- The improvement in S/N ratio offered by focussing the probe on the flaw is shown.



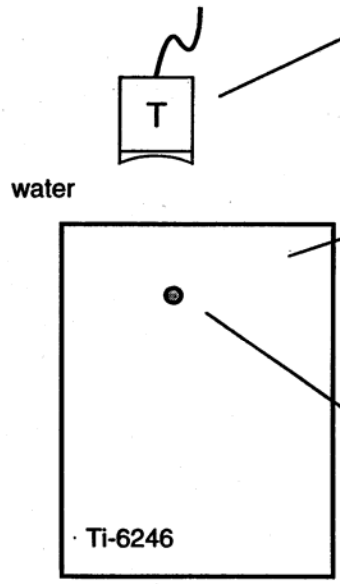
- The dependence of S/N ratio on flaw type is shown for a particular sample. The transducer is assumed to be focussed on the flaw. The simulated signal from a hard-alpha inclusion is 20 dB below that from either a flat crack or void of comparable size.



- The S/N ratio for the same simulated hard-alpha inclusion in two different specimens is shown.

IV. UNIFYING THEME:
ABILITY TO CONDUCT PARAMETRIC STUDIES

- An important practical use of models in conducting parametric studies is to determine how flaw signal levels are influenced by changes in inspection parameters.



Focussed Transducer

focal length = 3 inches in water
diameter = 0.5 inches

Emits 15-MHz pulse of ~ 1-μs duration

Isotropic specimen

density = 4.64 gm/cm^3
V-long. = 0.602 cm/μs
V-shear = 0.305 cm/μs
attenuation = 0.10 nepers/cm at 15-MHz

Low noise alloy having
Figure-of-Merit = 0.008 $cm^{-1/2}$

Flaw :

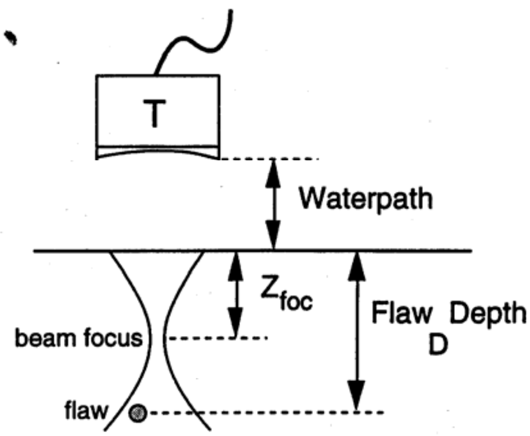
1.0 cm below top surface.

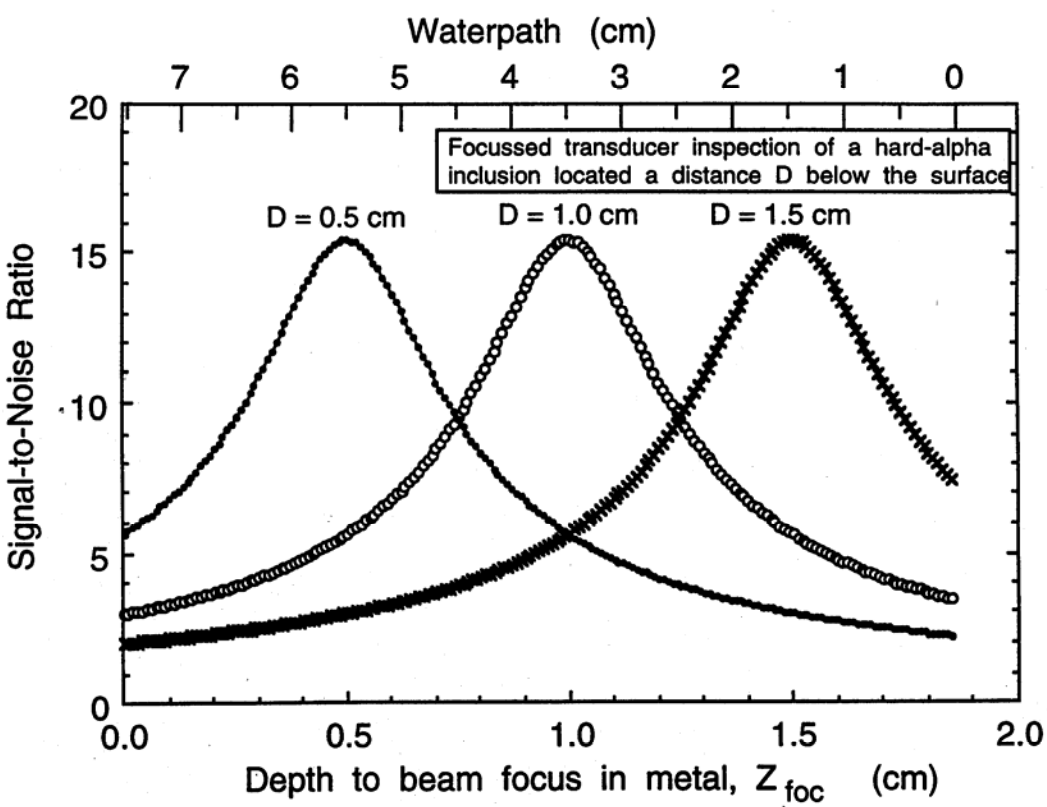
Spherical hard-alpha inclusion.

density = 4.59 gm/cm^3
V-long = 0.650 cm/μs
V-shear = 0.329 cm/μs

Diameter = 1 millimeter

- An example of a computation to determine the variation of S/N ratio with the position of the beam focus with respect to the flaw.



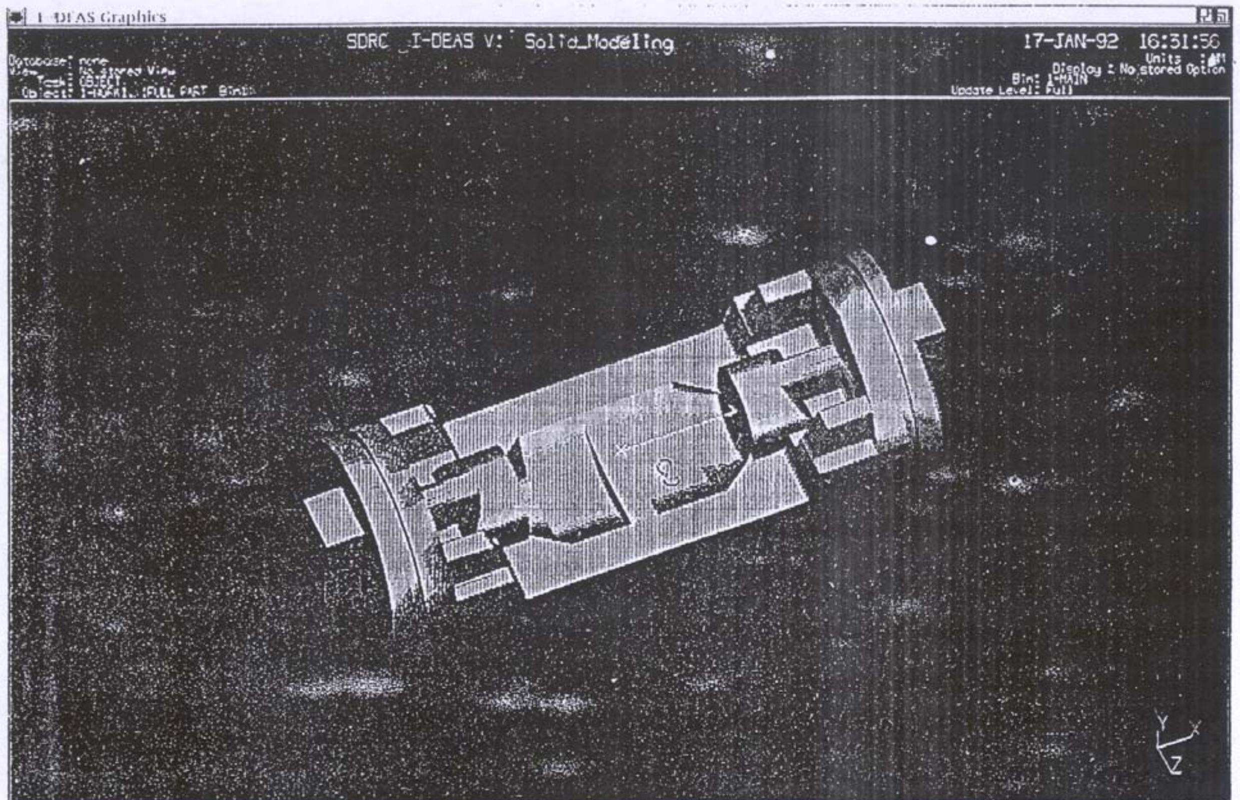


- Results, for three flaw depths, showing how S/N ratio peaks when beam focus approaches flaw.

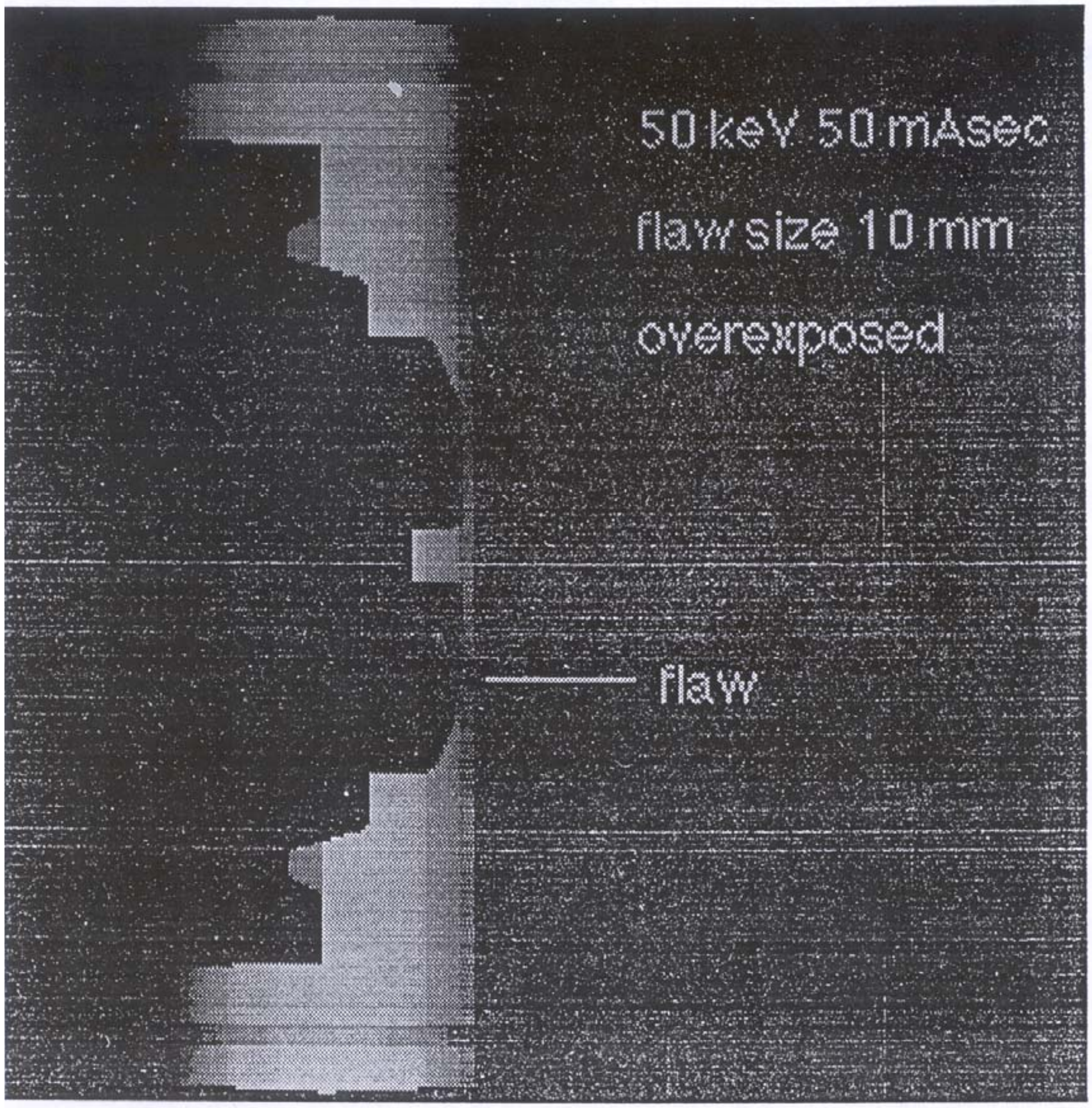
- The next series of pages show a CAD model of an automobile air-conditioner component, followed by simulations of its images for various current-exposure time products. Apologies are offered for the fact that the original images will likely reproduce poorly.

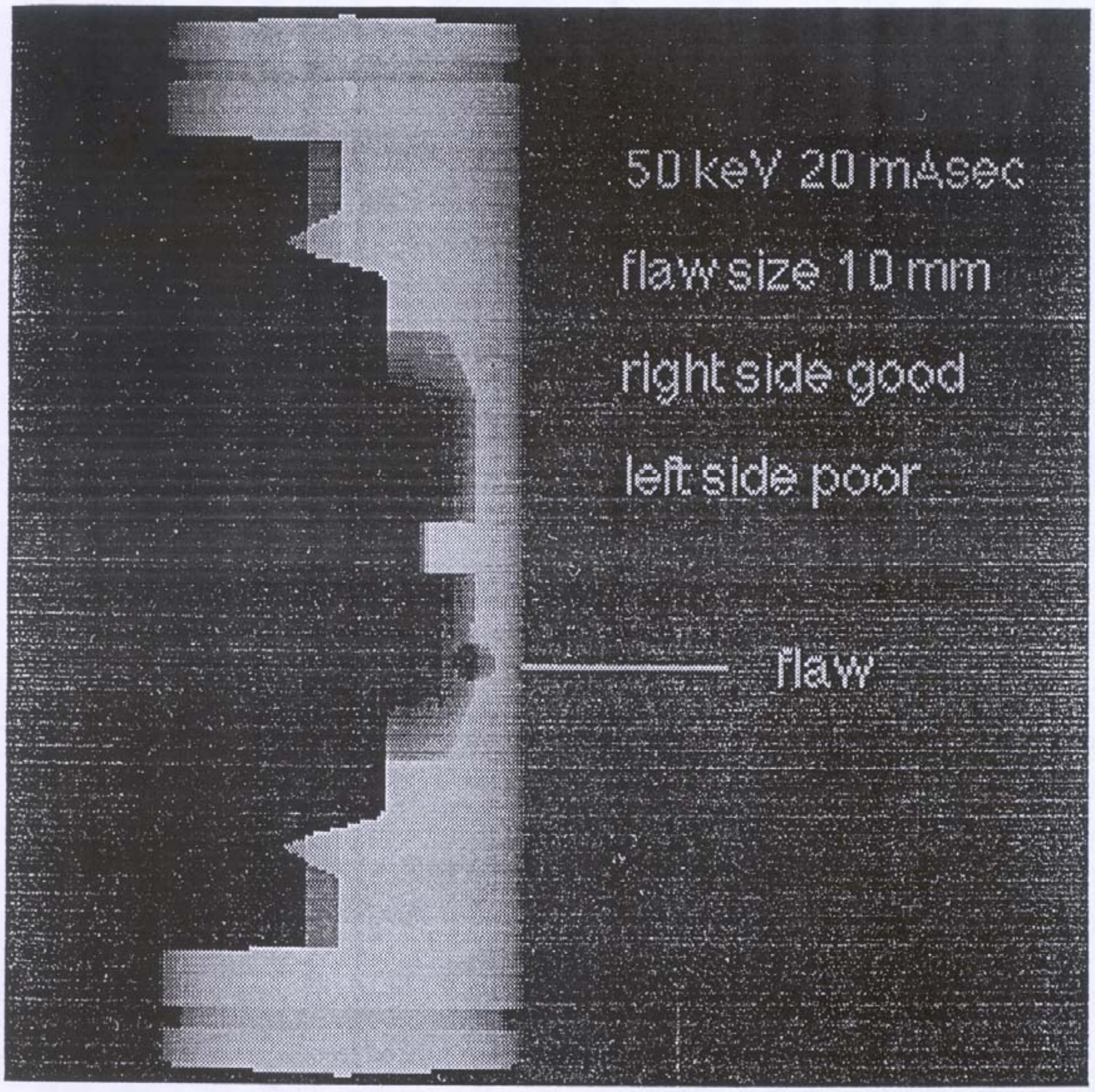
Reference

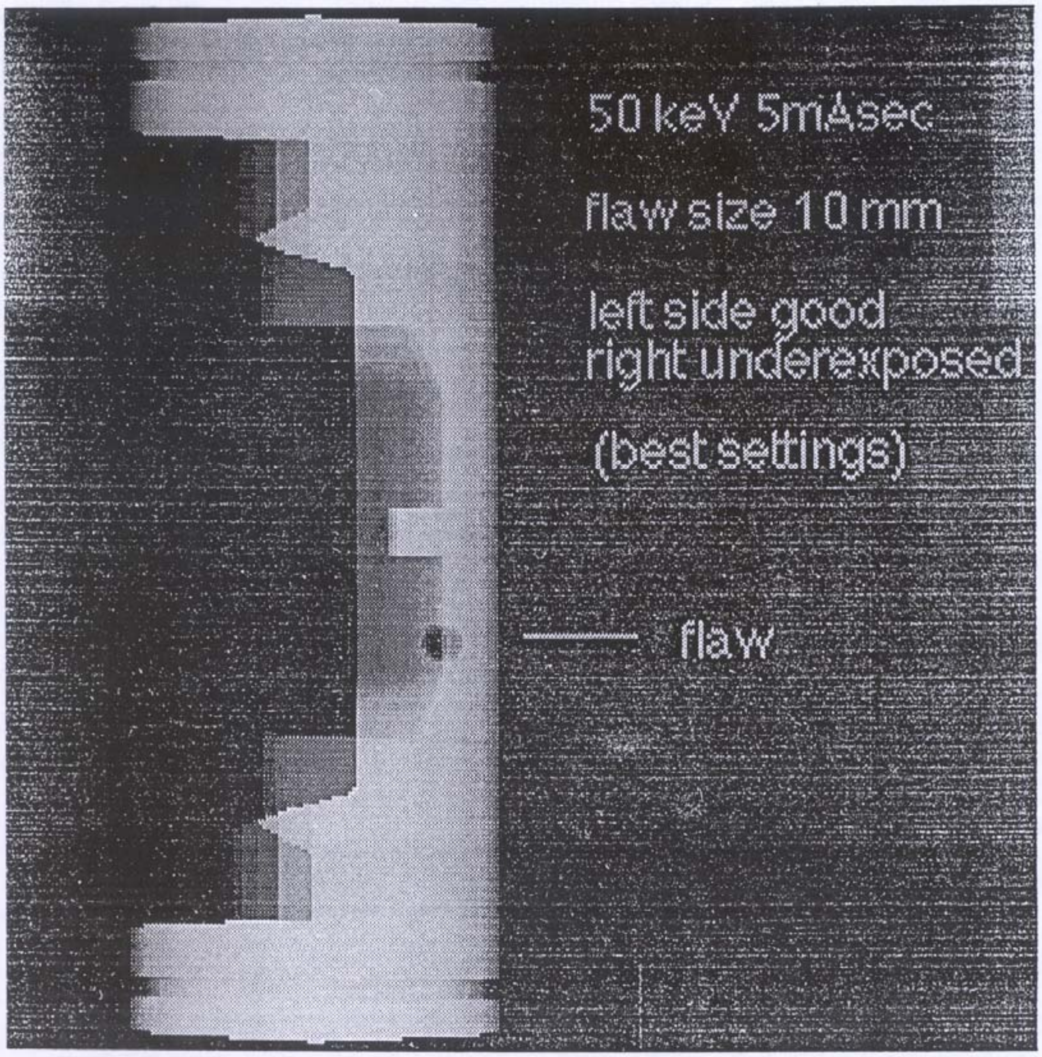
J. N. Gray, Center for NDE, Iowa State University, unpublished results.

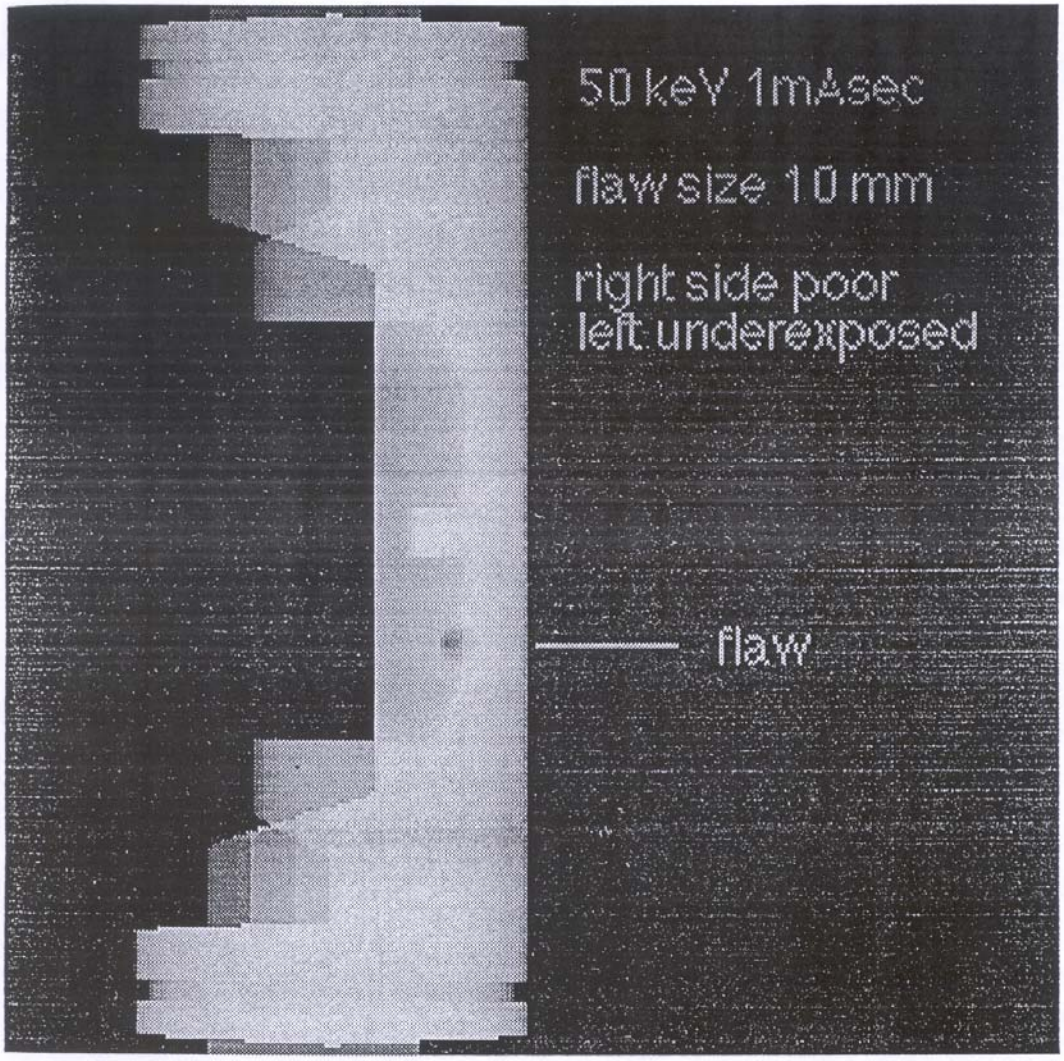


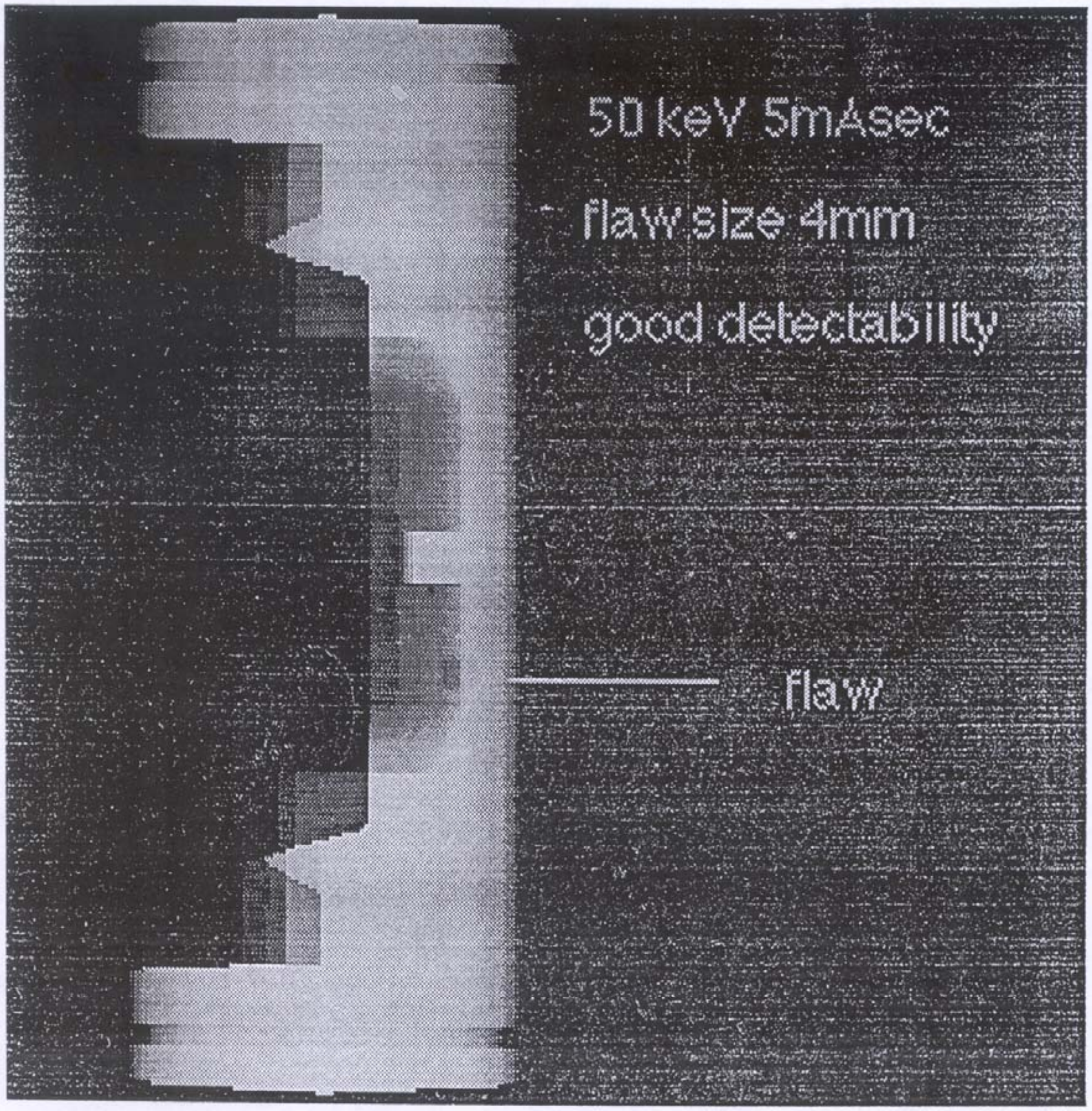
CAD Model

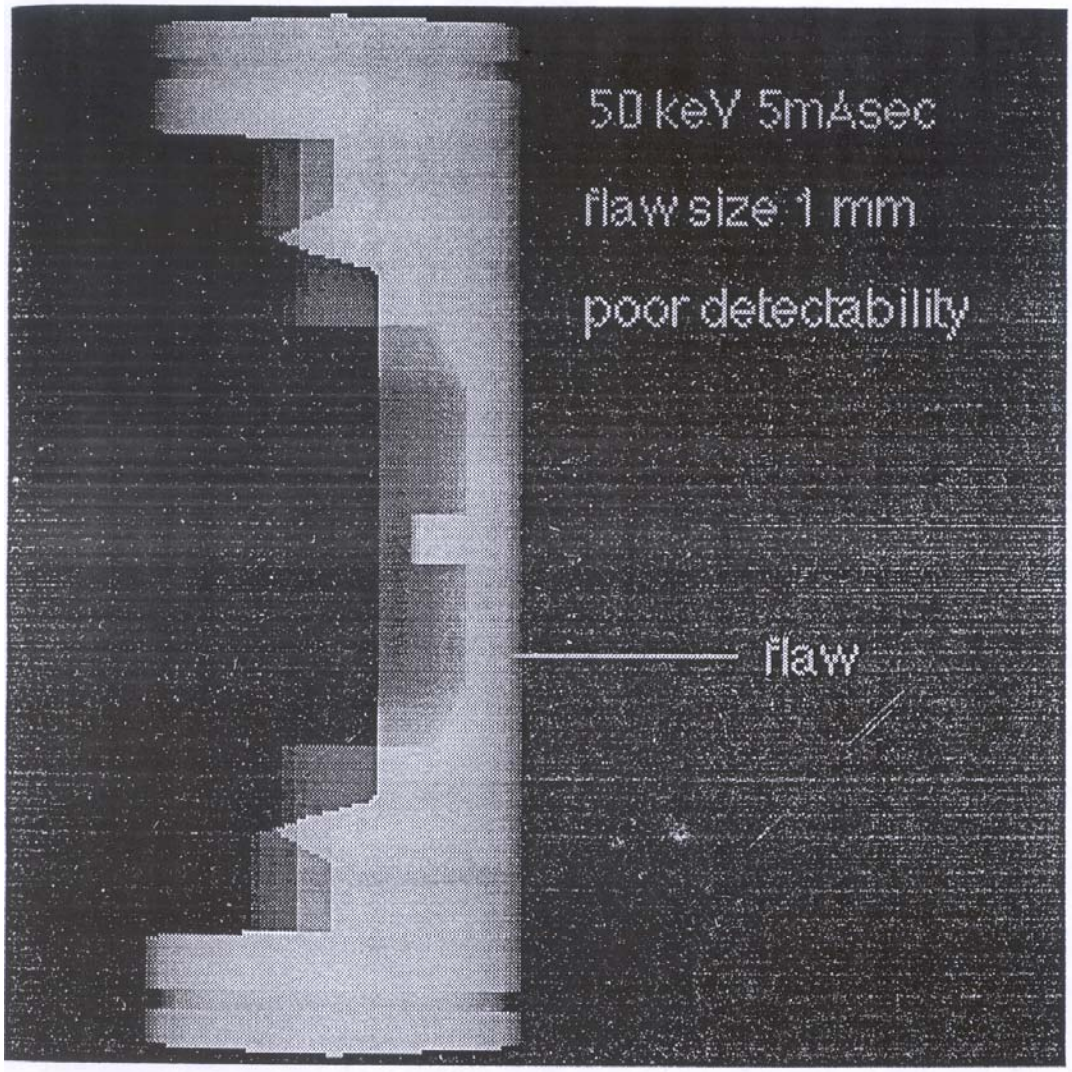

50 keV 50 mAsec
flaw size 10 mm
overexposed
flaw


50 keV 20 mAsec
flaw size 1.0 mm
right side good
left side poor
flaw


50 keY 5mAsec
flaw size 10 mm
left side good
right underexposed
(best settings)
flaw


50 keV 1mAsec
flaw size 1.0 mm
right side poor
left underexposed
flaw


50 keV 5mAsec
flaw size 4mm
good detectability
flaw


50 keV 5mAsec
flaw size 1 mm
poor detectability
flaw

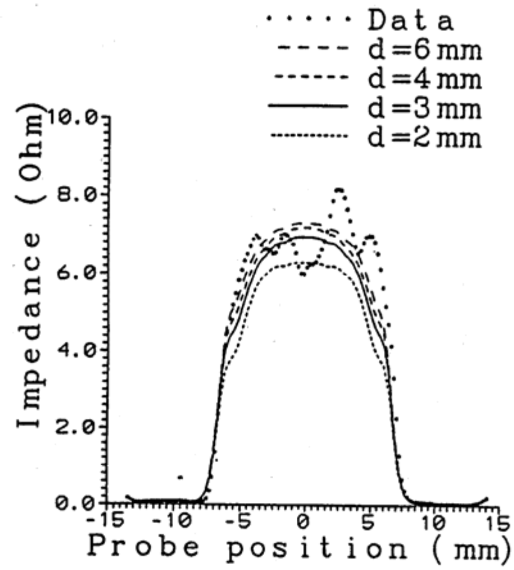
- Parametric studies can also be conducted in which flaw parameters are varied so that the model predictions fit experimental data. The following page illustrates determination of flaw depth (given surface breaking length) by fitting the eddy current impedance shift.

Reference

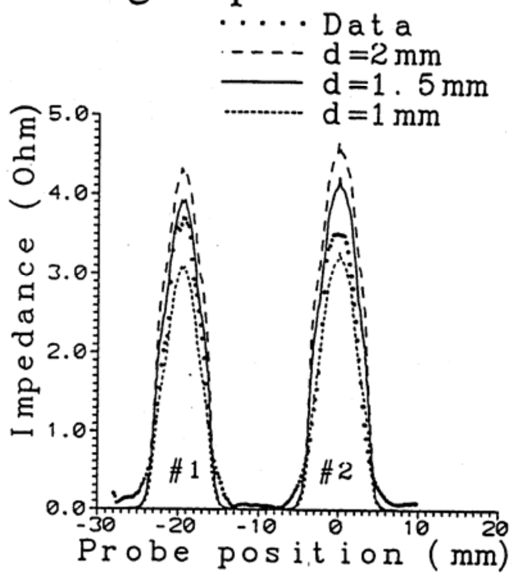
N. Nakagawa, Center for NDE, Iowa State University, unpublished results.

Flaw Sizing

Fatigue specimen "1"

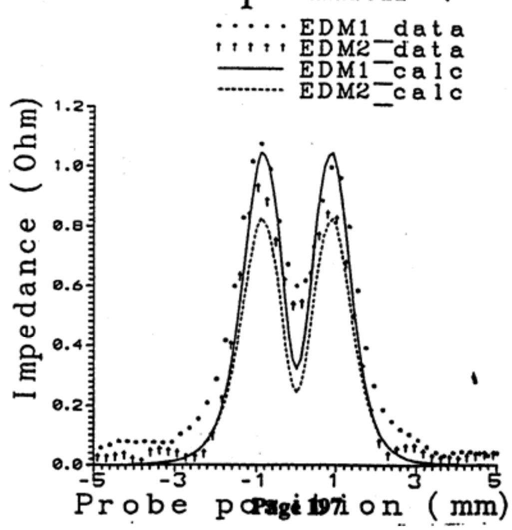


Fatigue specimen "2"



Specimen	Crack	Estimated length (mm)	Estimated depth (mm)
"1"	#1	12.9	> 3
"2"	#1	6.1	1.3 (0.05)
"2"	#2	6.9	1.2 (0.05)

cf. EDM specimen "7"



V.APPLICATION TO PROBABILITY OF DETECTION

A. FIRST PRINCIPLES APPROACHES

- In a first principles approach, one tries to estimate the POD that will be observed in a given experimental situation, requiring knowledge of both flaw and noise signal distributions. First principles approaches are useful in the design of inspection systems or in component design for inspectability.

- A calculation of the probability of detection (POD) depends on knowledge of the statistical distribution of both signal strength (from flaws of the same nominal size) and noise. Given these distributions, one can predict (for a specified acceptance criteria) the probability of making a positive call. The following page conceptually illustrates this for eddy currents. The top part shows the distribution of signals that might be observed when the probe is on the flaw (A) or off the flaw (B). The bottom shows an acceptance window (the square). The POD is the integral of distribution A over the window. The integral of distribution B over the window gives the probability of rejecting a flaw free part (probability of false alarm).

Reference

J. N. Gray, T. A. Gray, N. Nakagawa, R. B. Thompson, "Model for Predicting NDE Reliability," in Metals Handbook, 9th Ed., Vol. 17, Nondestructive Evaluation and Quality Control (ASM, Metals Park, 1989) pp. 702-715.

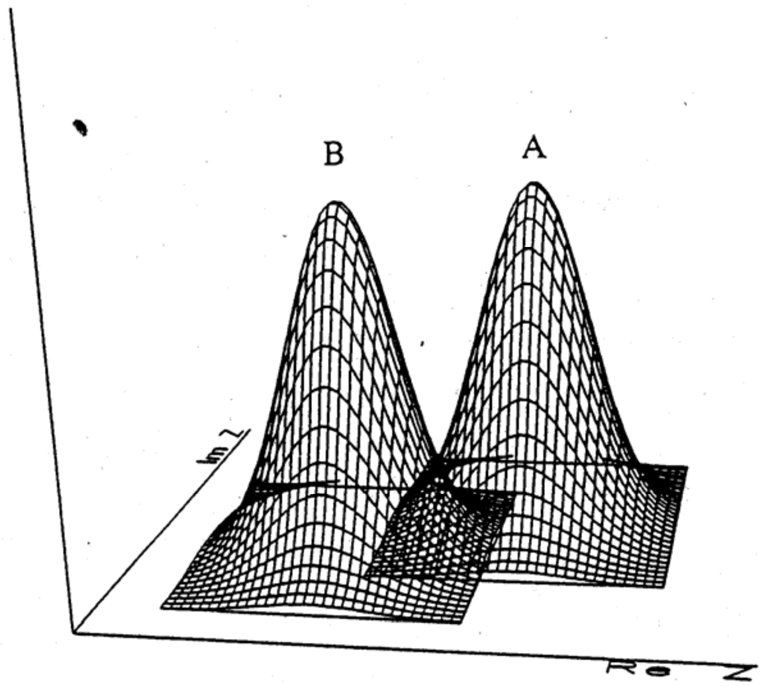


Fig. 7 Illustration of signal distributions. Measured impedance values will follow a certain distribution. Distribution A illustrates an on-flaw signal distribution (signals measured on a flaw), while B illustrates an off-flaw signal distribution.

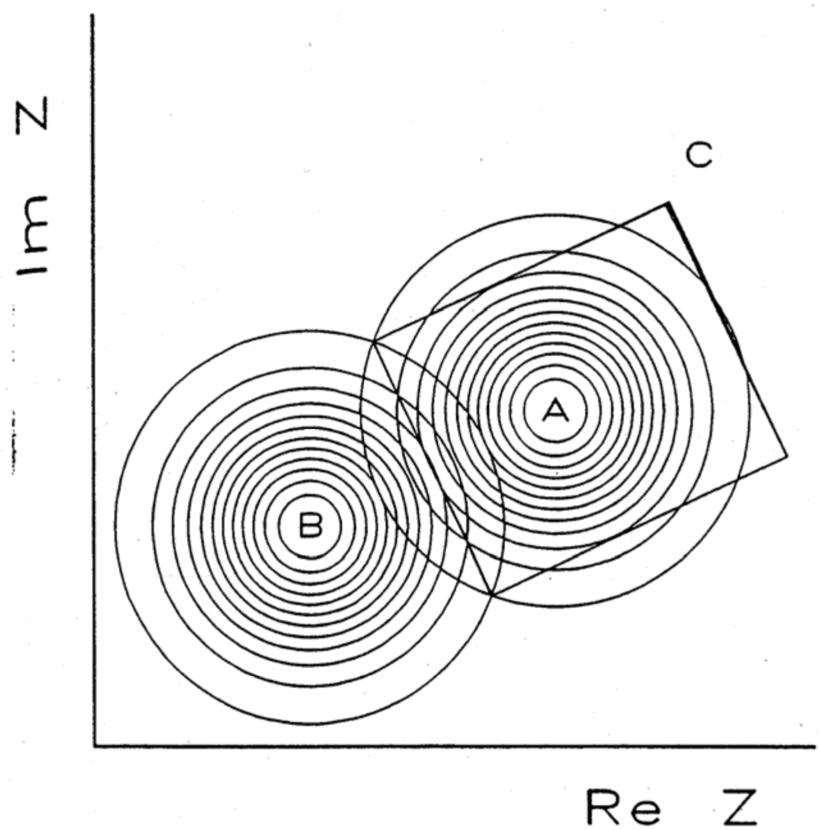


Fig. 8 The same distributions as in Fig. 7 viewed from above. Window C will be used to define POD and POFA as integrals of the distributions over C.

ASSESSMENT OF ENGINEERING TRADE-OFFS IN INSPECTION SYSTEM DESIGN

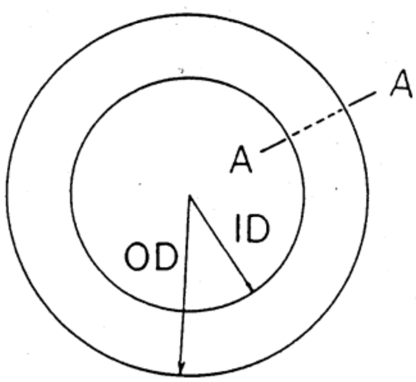
- The following three pages illustrate uses of ultrasonic models in trading off false-accepts versus false-rejects. The example problem under consideration is the inspection of an annular forging in which defects align with flow lines. This causes the defect orientation with respect to an ultrasonic beam of fixed angle to change throughout the part volume. The first page defines some of the problem parameters, the second page shows how the POD is influenced by changes in the threshold (the parameter on the curves) when the flaw is normal to the beam (0° tilt). The third page shows how changes in the flaw angle change the POD. (The angles on POD curves are angles of flaw normal with respect to illuminating beam.) In these simulations, flaw signal variability was induced by assuming that the flaw orientation was uniformly distributed (±5°) about the specified nominal value. It was concluded that a fixed probe angle could not produce adequate POD for the expected range of flaw angles, as dictated by flow lines.

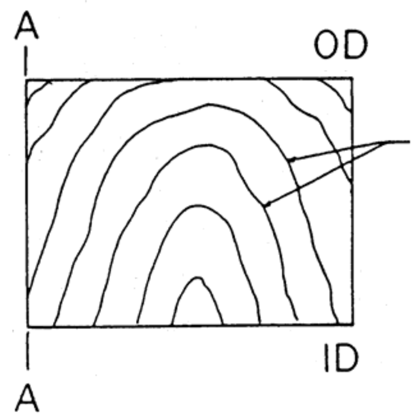
Reference

T. A. Gray, Center for NDE, Iowa State University, unpublished results.

TEST CASE #1 DETAILS

Component: Annular forging (steel)

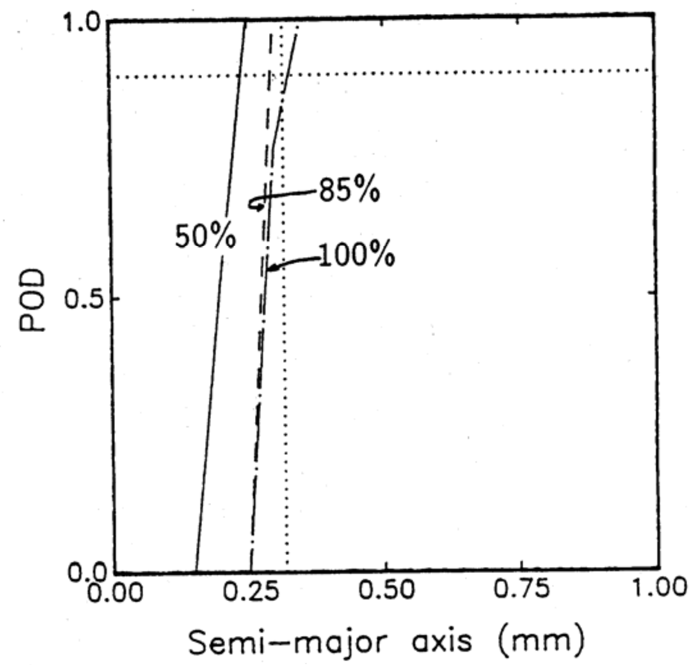




Defects:	Silicate inclusions alligned with forging flow lines.
Inspection problem:	Want to detect 0.025" diameter defects. Accept/reject decision is to scrap the component if a "flaw" is detected.
Candidate NDE system:	Ultrasonic scanning system with turntable and allowing vertical or radial indexing and probe articulation. Inspection is via video detection of backscattered signals.
Trade-offs:	What are FA/FR risks associated with scan speed, threshold, etc. selection? What are FR risks for high FA qualification? What are FA risks for low FR qualification?

CENTER FOR NDE

THRESHOLD SELECTION



Probe: 10 MHz planar
Water angle 7.2° (30° in solid)

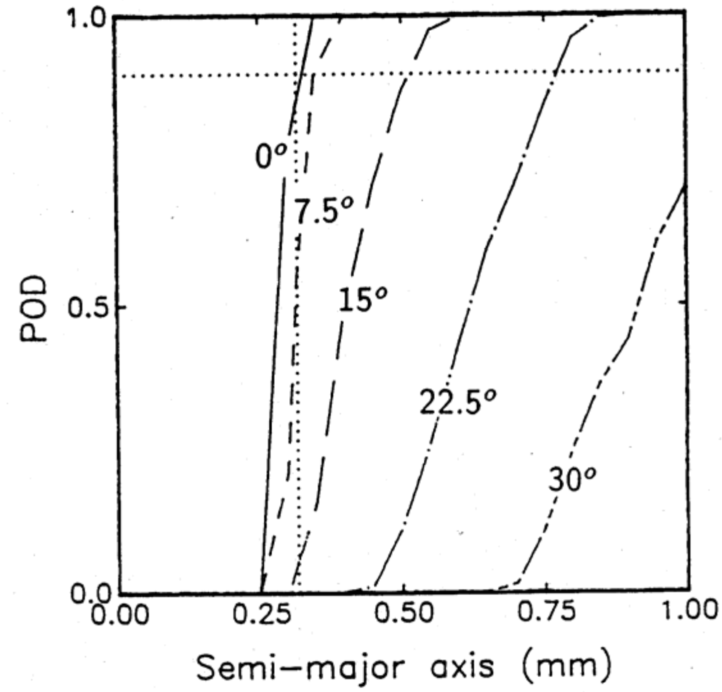
Defects: Tilted 0° (± 5°)

Scan Plan: Continuous rotational scan
Scan index = 0.10 inch

Threshold: Expressed as % #1FBH ⊥ to beam

Comments: All cases have adequate detectability, i.e. low FA. Lower thresholds produce higher FR.

FLAW TILT VARIABILITY



Probe: 10 MHz planar
Water angle 7.2° (30° in solid)

Defects: Random tilt and skew variability of ± 5° relative to mean orientation

Scan Plan: Continuous rotational scan
Scan index = 0.10 inch

Threshold: 100% #1FBH ⊥ to beam

Comment: Single fixed probe angle is unable to provide adequate detection reliability

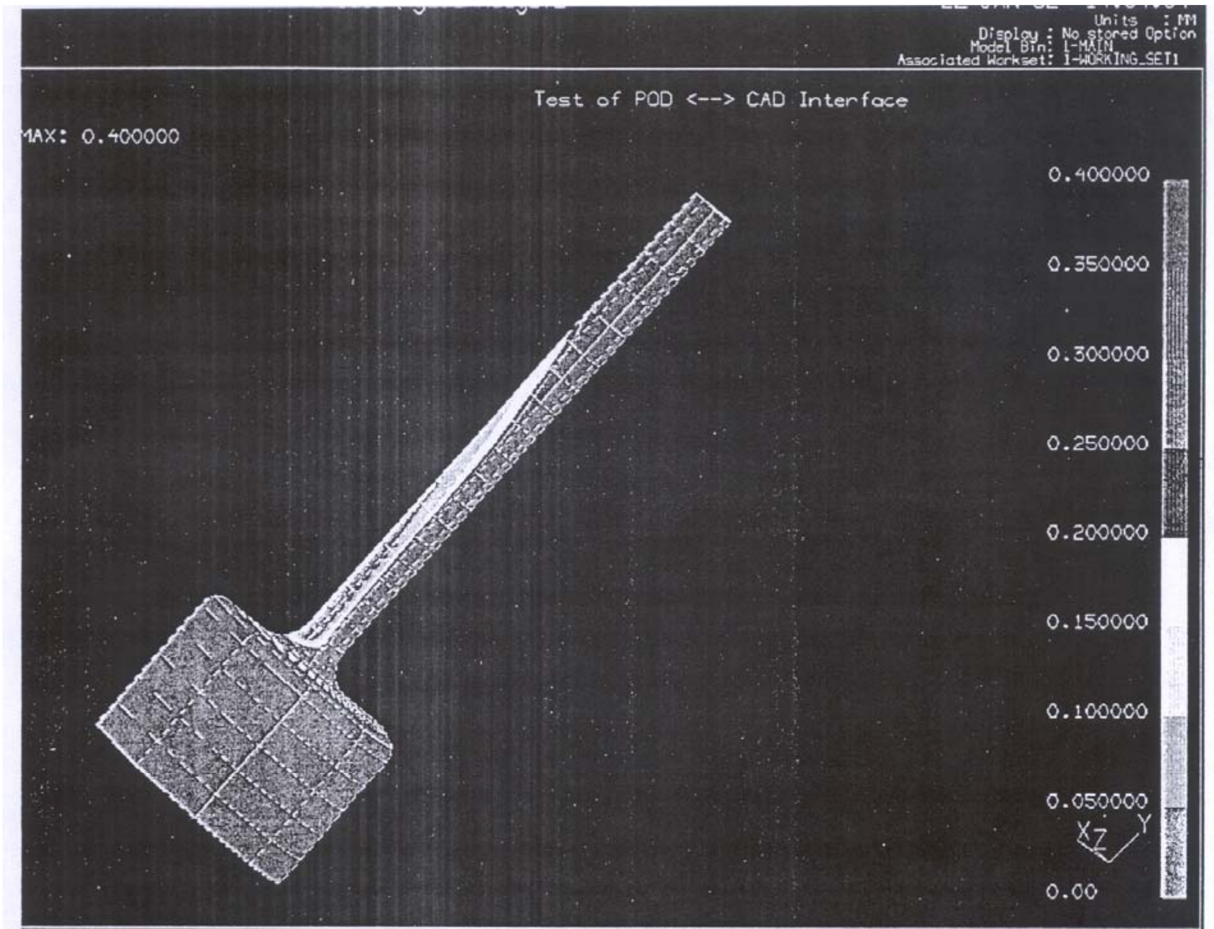
OPTIMIZATION OF INSTRUMENTAL SETTING

- To optimize an inspection, one needs to first specify the expected distribution of flaw sizes and then determine whether various instrumental settings will produce acceptable detection. The following three pages illustrate this process. The first shows a map of critical flaw sizes for a model "pin" geometry under a particular set of loading conditions. The second shows an x-ray simulation of the probability that these can be detected under optimal and over-exposure conditions. The third shows an ultrasonic simulation. Apologies are extended for the poor reproduction of the color originals.

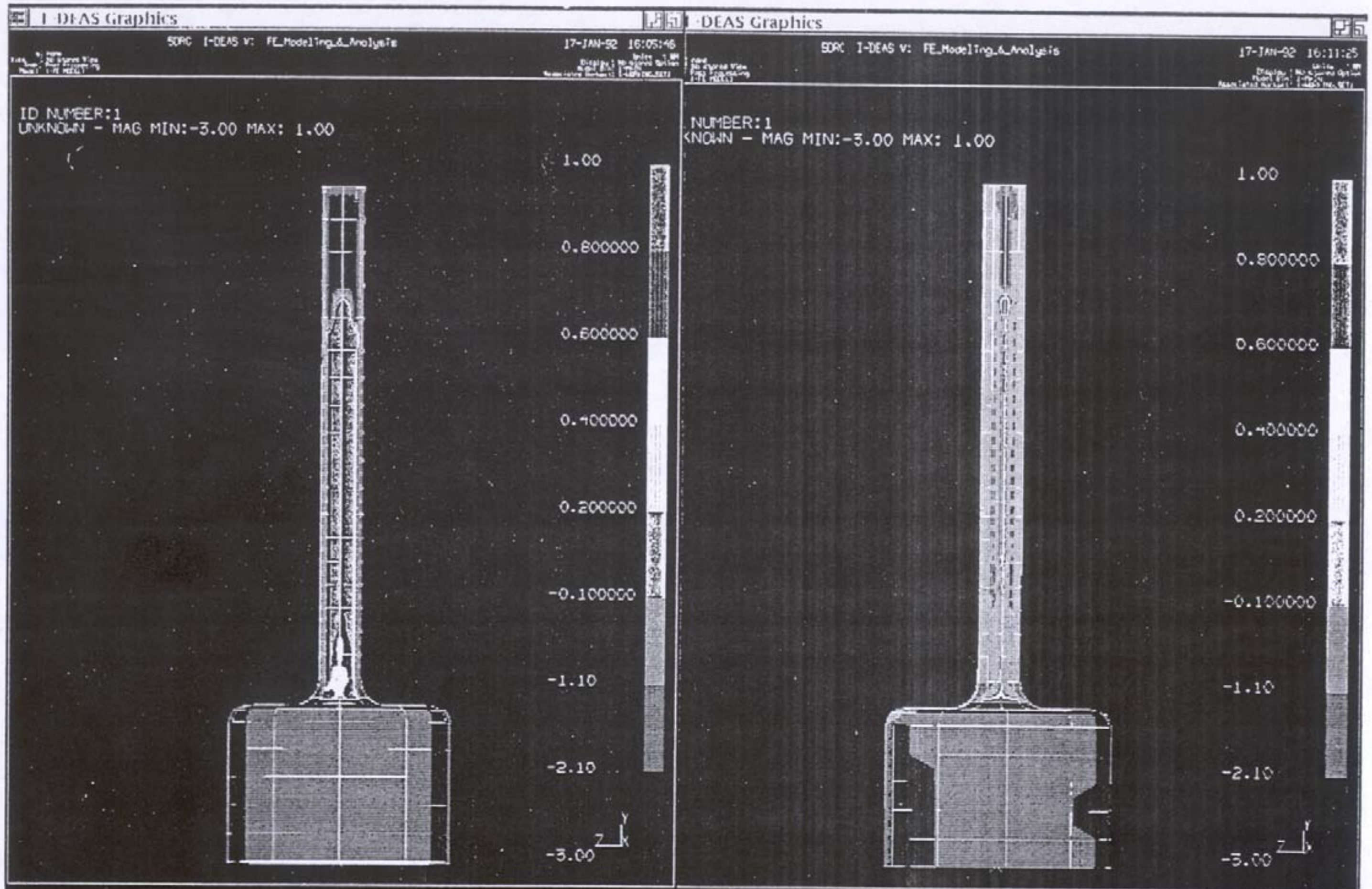
Reference

J. N. Gray, T. A. Gray, T. J. Rudolphi, L. W. Schmerr, Center for NDE, Iowa State University, unpublished results.

L. W. Schmerr and D. O. Thompson, "Incorporating Inspectability into Design: The New Role of NDE in Concurrent Engineering" in <u>NDE's Role in Concurrent Engineering</u> (ASME, NY, in press).

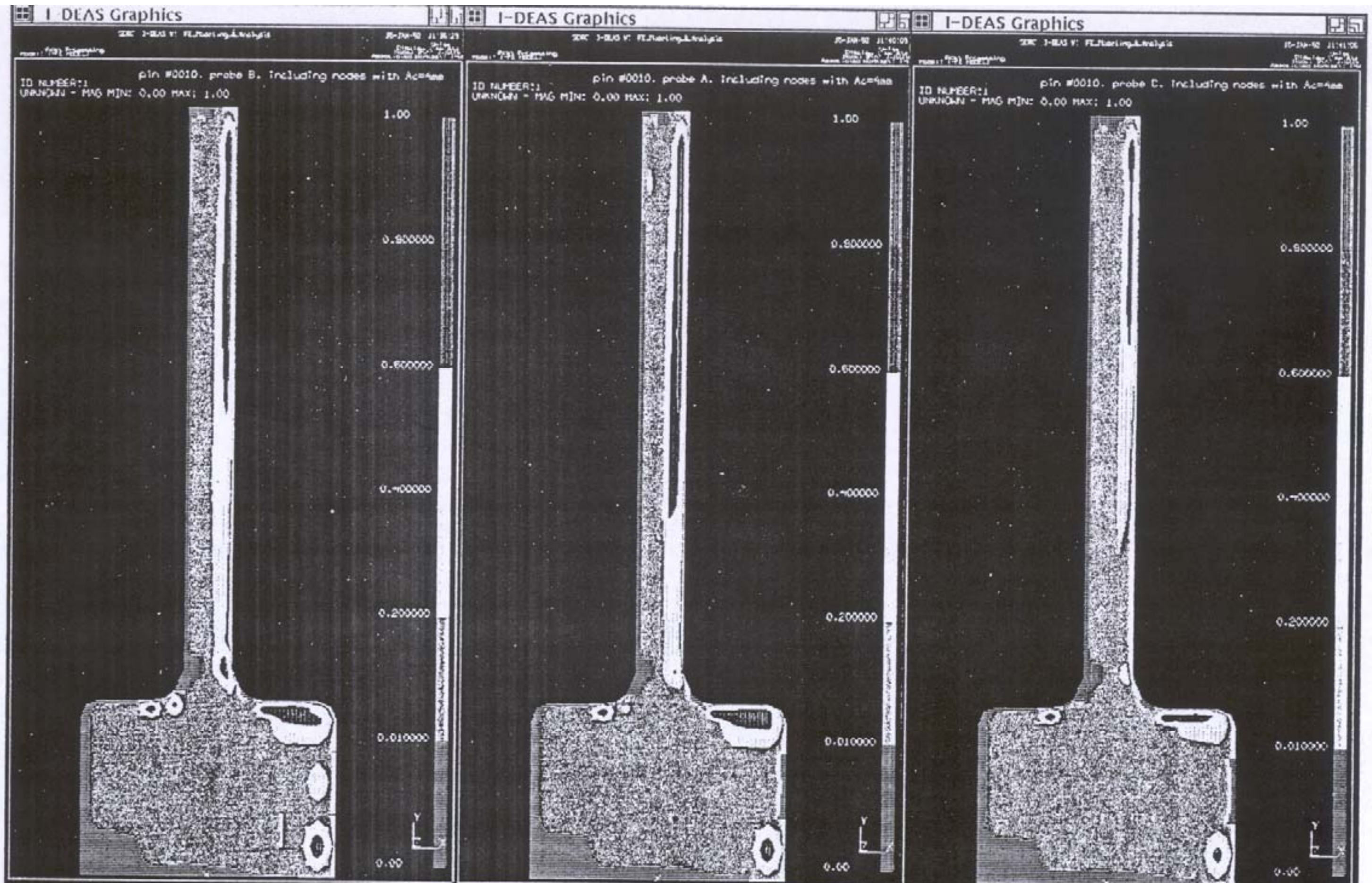


Critical Flaw Map



Optimal Exposure

Over–Exposure



5 MHz, F=4" 10 MHz, F=3" 15 MHz, F=3.8"

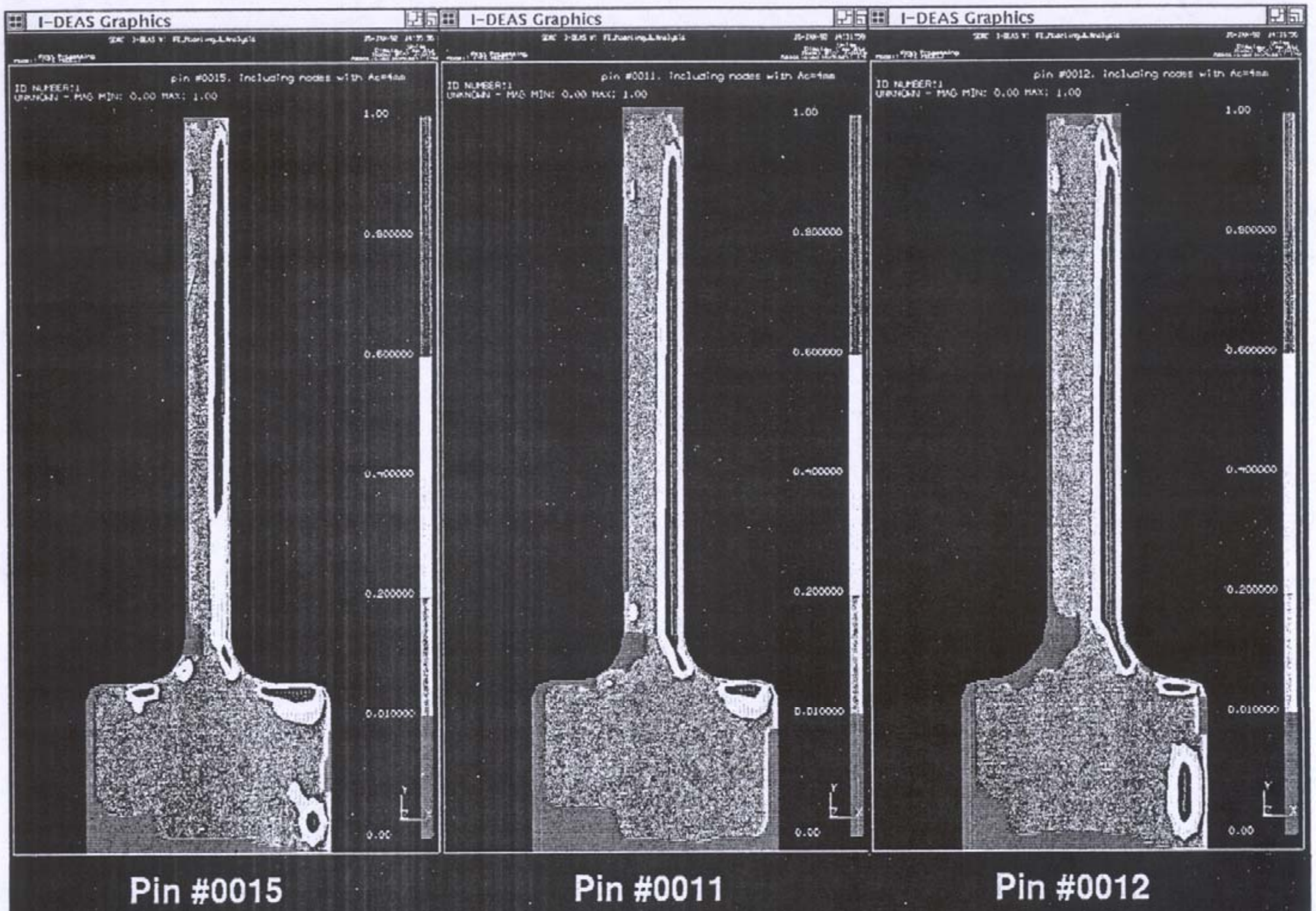
POD Comparisons for Different Inspection Parameters
Pin #0010; 30-degree L-wave; Interior Defects

PREDICTION OF THE EFFECTS OF CHANGE IN PART GEOMETRY (DESIGN FOR INSPECTABILITY)

- The following illustrates how the ultrasonic POD will change as one increases the fillet radius of curvature in the "pin". For each case, a critical defect map was first constructed, such as the one shown before, and then the POD for these particular defects was computed. As would be expected, the results show that improved inspectability is obtained by increasing the radius. This advantage must be traded off against other design considerations. Apologies are extended for the poor reproducibility of the color originals.

Reference

T. A. Gray, T. J. Rudolphi, L. W. Schmerr, Center for NDE, Iowa State University, unpublished results.



POD Comparisons for Different Pin Designs
10 MHz, F=3" Probe; 30-degree L-wave; Interior Defects

B. OTHER APPROACHES

- Models can also be used in demonstration programs when only a limited number of samples are available. Ongoing efforts in the nuclear power industry to this end were discussed in section III. More generic comments follow.

Reference

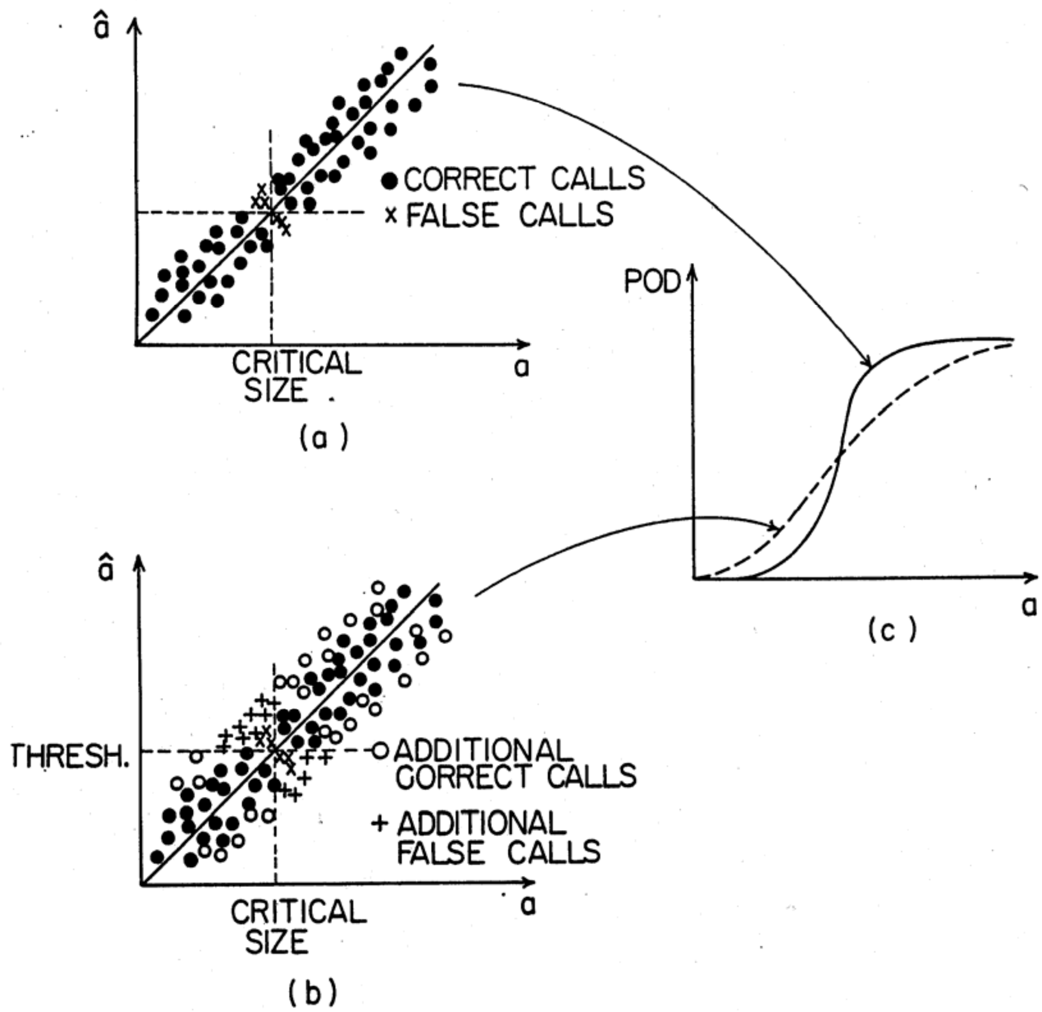
R. B. Thompson, D. O. Thompson, H. M. Burte and D. E. Chimenti, "Use of Field-Flaw Interaction Theories to Quantify and Improve Inspection Reliability," in Review of Progress in Quantitative NDE, Vol. 3, D. O. Thompson and D. E. Chimenti, Eds. (Plenum Press, NY, 1984) pp. 13-24.

Scenario for Extension of Demonstration Programs

1. Model validation. As noted at the beginning, the first step must always be a careful establishment of the range of appliability of the model. Given this, one can use it to augment experimental results. For example,

2. Demonstration Experiments. Suppose demonstration experiments have been performed under a limited set of conditions, leading to the $\hat{a}$ versus a shown in part (a) of the next page. Then a validated model can be used to simulate $\hat{a}$ versus a for other experimental conditions (e.g. flaw shapes or orientations expected in practice but not represented in the sample set) to generate the augmented $\hat{a}$ versus a data set shown in part (b).

3. POD. Analysis of the more complete data set would lead to a more realistic assessment of POD, as shown in part (c).



â
CORRECT CALLS
x FALSE CALLS
CRITICAL SIZE
a
(a)
POD
a
(c)
â
THRESH.
ADDITIONAL CORRECT CALLS
+ ADDITIONAL FALSE CALLS
CRITICAL SIZE
a
(b)

Relative Operation Characteristics

- In the fourth paper of this series, Sturges discussed the relative operating characteristic (ROC) approach to POD. In this approach, a key factor is the S/N ratio expected in particular inspection situations. Use of models to simulate S/N ratios, as illustrated in sections III and IV of this paper, can form an important component of an ROC approach.

VI. CONCLUSIONS

- Models have a wide role in POD studies. They can be utilized in a variety of modes ranging from parametric studies to first principles POD predictions. These engineering tools can be used to evaluate existing inspection systems, design new inspection systems and ultimately enable an engineer to design for inspectability.