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Annual Report 1979 Office of Nondestructive Evaluation

Harold Berger and Leonard Mordfin, Editors

Office of Nondestructive Evaluation
National Measurement Laboratory
National Bureau of Standards
U.S. Department of Commerce
Washington, DC 20234

November 1979

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Luther H. Hodges, Jr., ***Deputy Secretary***
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Preface

This report is the second in the series of annual reports on the National Bureau of Standards (NBS) program in nondestructive evaluation (NDE). These reports summarize the program's activities and plans. The focus of the present report is on the program's activities in Fiscal Year 1979 and on its plans for the next five years.

It is hoped that this report will provide useful information to the technical community about the present directions of the NBS effort in nondestructive evaluation. We recognize that comments and suggestions from manufacturers and users of NDE equipment can provide guidance for the NBS program. We encourage readers to share with us their needs and interests in the field of nondestructive evaluation.

Harold Berger
Chief, Office of
Nondestructive Evaluation

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INTRODUCTION

Today, many material failures are prevented thanks to a system of test methods that detects flaws and defects in materials before the failures occur - in fact, before the materials are put into service. Called "nondestructive evaluation (NDE)," the system is potentially applicable to inspection of such high technology products as nuclear reactors and supersonic aircraft as well as to inspection of more consumer-oriented products such as pacemakers and parts of automobiles.

Actually, NDE is not a single method, but rather a name used to describe a variety of techniques that can be used to examine materials without destroying or damaging them during the examination procedure. Some of these methods, x-radiography for example, have been used for many years. Others, such as neutron radiography and acoustic emission, are just now coming into wider use as NDE methods. A comparison of the common NDE methods is given in Table I.

The past year has brought about a striking upsurge in national awareness of NDE. The problem of aircraft maintenance and inspection, as related to the DC-10 airplane, attracted a great deal of attention to NDE. NBS was one of several organizations interviewed by Science magazine to gather background material for its important summaries of the NDE situation.*

A potentially serious national problem in which NBS has become deeply involved concerns the probable use of "soft" aluminum in several air and space craft. For the past 2-1/2 years, a major manufacturer has inadvertently produced aluminum-alloy plate that is believed to contain regions of inadequate strength. It is suspected that some of this material has already been fabricated and put into several commercial and military airplanes and the space shuttle. The problem that NASA brought to NBS involves metallurgy (identify the metallurgical problem and fabricate well-characterized specimens for mechanical and nondestructive evaluation), NDE (correlate the NDE measurements with the material parameters) and statistics (assure a statistically valid conclusion from the tests). This short-term project, now underway, will provide technical information to help guide NASA. There is also a longer-term project planned; this supports existing NBS-NDE plans to improve our understanding of (and contribution toward) NDE characterization of materials.

Other newsworthy events in the past year also helped to keep NDE in the public eye. The accident at Three Mile Island pointed up deficiencies in nuclear power plants. It is now recognized that nondestructive inspections to guarantee the integrity of the pressure boundary may not be adequate to prevent all accidents; nondestructive methods for verifying the

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1. A. L. Robinson, "New Testing Methods Could Boost Air Safety," Science, 205, 29-31 (July 6, 1979).
2. A. L. Robinson, "Making Nondestructive Evaluation a Science," Science, 205, 477-479 (August 3, 1979).

inservice performance of pumps, valves and instrumentation are urgently needed. The leaks that appeared in the Trans-Alaska oil pipeline (mainly due to settling problems) were not the result of faulty girth welds. Yet, undoubtedly, these leaks recalled to people's minds the NDE problems with girth welds that occurred during construction. In this area, NBS has a continuing involvement; new DOT support for NBS, to study fracture and NDE problems for the new gas line to come through Canada, has recently been finalized.

There were other important, although perhaps less newsworthy, NDE events. The Electric Power Research Institute (EPRI) initiated a new NDE Center to help transfer NDE research technology so it can be put to use by the electric utilities. A new emphasis on NDE is appearing at Iowa State University and a major new commercial force in the field was set up in Albuquerque, as major changes took place in the Rockwell International program in NDE.

It is reassuring that throughout these occurrences the NBS activity in NDE has been recognized and called upon often. This makes it all the more imperative that the NDE activity at NBS address real issues.

The principal emphasis in the NDE Program during Fiscal Year 1979 remained on standards and measurement activities that will provide near-term improvements in the major NDE methods. Thus, calibration services or Standard Reference Materials (SRM's) are, or will shortly be, available for ultrasonic reference blocks, ultrasonic transducers (total power, radiation force as a function of frequency), electrical conductivity (ac and dc), a penetrant sensitivity crack plate, measurements of fluorescent brightness for penetrants and magnetic particles, radiographic film density step tablets (SRM's to provide a density range beyond 4.0 are under consideration) and measurements of an inspector's visual acuity. In addition, calibration of acoustic emission transducers is now being offered on a limited basis. These efforts will improve the reproducibility of NDE measurements. On a longer-term basis, the program has begun to address the nondestructive characterization of material parameters and defects, in order to improve the quantitative nature of NDE measurements. In this connection, a milestone for the coming year concerns the underlying theory for an ultrasonic tomography system that will read out in terms of ultrasonic velocity, attenuation and scattering. Such an instrument will be useful for characterizing both defects and material properties. This is one example to demonstrate that the program has initiated work to address needs for quantitative NDE and characterization of materials. These efforts will increase as we complete the task of providing improved measurements and procedures for the well-used NDE methods. Future activities will also address changes in NDE methods and standards that may come with automated test systems.

Table I

COMPARISON OF COMMON NONDESTRUCTIVE EVALUATION METHODS

Method	Characteristics Detected	Advantages	Limitations	Example of Use
Ultrasonics	Changes in acoustic impedance caused by cracks, nonbonds, inclusions, or interfaces.	Can penetrate thick materials; excellent for crack detection; can be automated.	Normally requires coupling to material either by contact to surface or immersion in a fluid such as water.	Adhesive assemblies for bond integrity.
Radiography	Changes in density from voids, inclusions, material variations; placement of internal parts.	Can be used to inspect wide range of materials and thicknesses; versatile; film provides record of inspection.	Radiation safety requires precautions; expensive; detection of cracks can be difficult.	Pipeline welds for penetration, inclusions, voids.
Visual-Optical	Surface characteristics such as finish, scratches, cracks, or color; strain in transparent materials.	Often convenient; can be automated.	Can be applied only to surfaces, through surface openings, or to transparent material.	Paper, wood, or metal for surface finish and uniformity.
Eddy Currents	Changes in electrical conductivity caused by material variations, cracks, voids, or inclusions.	Readily automated; moderate cost.	Limited to electrically conducting materials; limited penetration depth.	Heat exchanger tubes for wall thinning and cracks.
Liquid Penetrant	Surface openings due to cracks, porosity, seams, or folds.	Inexpensive, easy to use, readily portable, sensitive to small surface flaws.	Flaw must be open to surface. Not useful on porous materials.	Turbine blades for surface cracks or porosity.
Magnetic Particles	Leakage magnetic flux caused by surface or near-surface cracks, voids, inclusions, material or geometry changes.	Inexpensive, sensitive both to surface and near-surface flaws.	Limited to ferromagnetic material; surface preparation and post-inspection demagnetization may be required.	Railroad wheels for cracks.

PERSONNEL

The Office of Nondestructive Evaluation is a program office coordinated within the NBS National Measurement Laboratory (NML). (An organization chart for NML is given in the Appendix.) NDE projects, however, are undertaken throughout the Bureau. Present NDE activities involve all five centers in the National Measurement Laboratory and four centers in the Bureau's National Engineering Laboratory. Work is done at the Bureau laboratories in Gaithersburg, Maryland and in Boulder, Colorado.

NDE projects are started on the basis of need as determined by discussions with people from industry, technical societies and government agencies. Once a project is decided upon, the work is initiated following agreements on scope and schedule with NBS staff and Center or Division management. Occasionally, projects are conducted or supplemented by outside sources.

A diagram showing the personnel in the Office of NDE for the entire period of FY1979 is given in Figure 1. During this past year our efforts were supplemented by a visiting engineer, S. Golan of the Israel Institute of Metals, by two guest workers, Sekyung Lee of the Korea Standards Research Institute and Clifford Anderson of the Naval Surface Weapons Center in Dahlgren, Va., and by a student trainee from the College of Notre Dame in Baltimore, Amelia Nunn. All have returned to their host organizations. In addition, our office staff was temporarily assisted by Diane Frizzell, now assigned elsewhere at NBS.

The leaders of the technical activities within the NBS Centers are listed in Table II; the listing is given in terms of technical areas.

Office of Nondestructive Evaluation

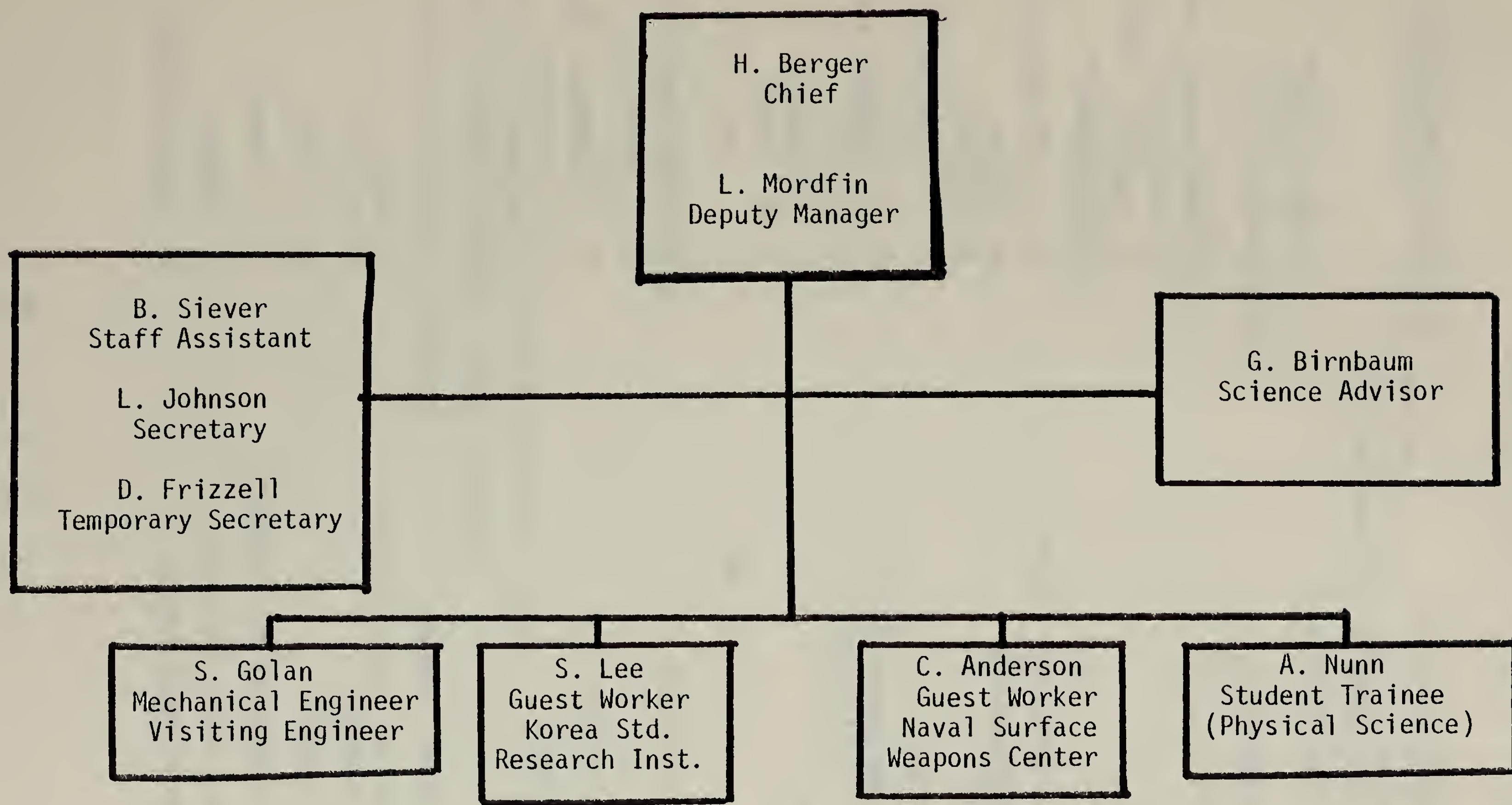

Figure 1. The Office of NDE; personnel participation during FY1979.

Table II

Tabular Summary of
NBS - NDE Personnel

Technique or Area	Principal Investigators
A. Acoustic - Ultrasonic Application to:	
Building Materials	J. R. Clifton R. G. Mathey
Inorganic Materials	E. R. Fuller
Metals	J. A. Simmons H. Ledbetter*
Polymers	B. Fanconi R. E. Green+
Crack Characterization	D. J. Chwirut
Instrumentation	M. Linzer S. Edelman N. V. Frederick*
Standards	
Reference Blocks	D. G. Eitzen
Transducers	N. N. Hsu
Theory	J. A. Simmons R. B. Clough
B. Radiography	
Neutron Radiography	D. A. Garrett C. D. Bowman
Real-Time Systems	M. Kuriyama
X-Radiography	R. C. Placious J. W. Motz D. Polansky
C. Electromagnetic Methods	
Electrical, Eddy Current Methods	G. Free B. M. Field
Theory	A. H. Kahn
Conductivity Standards	L. H. Bennett
Visual Acuity Standards	G. Yonemura
Magnetic Measurements	L. Swartzendruber

Microwaves	D. Ellerbruch*
Optics	A. Feldman E. C. Teague
D. Penetrants	
Brightness, Fluid Properties	B. F. Howell K. D. Mielenz R. Velapoldi
Crack Standard	F. Ogburn
Flow Characteristics	S. Deutsch
E. Wear Debris Analysis	A. W. Ruff
F. Thermal Tests	
Microcalorimetry	E. J. Prosen
G. Fracture	B. W. Christ* M. B. Kasen* J. H. Smith
H. Statistics	J. T. Fong
I. Leak Testing	S. Ruthberg

+ WAE, Part-time

* NBS Boulder Laboratories

Telephone Numbers:

NBS, Gaithersburg, Maryland, (301) 921-1000
NBS, Boulder, Colorado, (303) 499-1000
Office of NDE, (301) 921-3331

OVERVIEW OF THE TECHNICAL PROGRAM

Despite the increasing use of NDE methods for practical purposes, there are definite needs to improve the measurement methods and to relate measurements to the actual performance of the material. The Office of Nondestructive Evaluation was established by the National Bureau of Standards to assist industry and government agencies in improving the reliability of materials and structures; NBS is working to help industry develop methods for accurate and reproducible NDE measurements. This includes technical investigations, development of standards (both measurement standards and procedural documents), characterization of instruments, and assessments of the meaning of NDE measurements in relation to material performance. The main emphasis of the NBS program is on the needs for improved measurements and calibration standards and procedures for many of the NDE methods commonly used in industry.

At the Bureau the NDE program is coordinated by the National Measurement Laboratory. Strong interactions with industry, technical societies, and government agencies have been established in order to solicit their advice on needs and to aid in technology transfer for developed methods and standards.

An overview of the NBS technical program in NDE is presented below. More detailed reports of recent progress in selected areas of the program are provided in the next section of this report.

Acoustic-Ultrasonic Programs

Work is in progress to develop methods for calibration of ultrasonic and acoustic emission transducers. Spectral characteristics, beam profile, and total sound power measurements are being studied. Some transducer calibration services are now available.

NBS researchers are studying ultrasonic test blocks, in a program that had initial, partial funding from the Air Force, Army, and the National Aeronautics and Space Administration, to determine the reasons for variability of these metal calibration blocks. A calibration service for aluminum ultrasonic reference blocks is available. Service for steel ultrasonic reference blocks is planned for announcement in December 1979; work on titanium blocks is progressing. Futher directions for this effort include the development of material-independent test blocks and the development of well-characterized fatigue cracks that could serve as a calibration artifact for many NDE tests.

Instrumentation development work in both ultrasonics and acoustic emission is also in progress. This includes development of improved signal-to-noise ratio systems by methods such as signal averaging and pulse compression. A program to characterize the important variables in ultrasonic instrumentation is in progress. Imaging instrumentation is also under development.

These NDE methods are being applied to metals, ceramics, polymers, building materials, and electronic components. Specific application studies involve ultrasonic inspection of pipeline welds for the Department of Transportation and the analysis of ultrasonic inspection data for the U.S. Nuclear Regulatory Commission.

A program to develop a theoretical basis for acoustic emission spectral analysis to characterize moving cracks or defects is in progress, partially funded by the Electric Power Research Institute. This program includes work for improved transducer calibration.

Radiography

Current programs involve work in both neutron and x-radiography. The x-ray program includes investigations of standards for the measurement of spatial resolution in radiographic systems, for the determination of response of x-ray film and for the characterization of real-time fluoroscopic systems. Developments in progress include work on improved x-ray screens and determination of scattered radiation content and its effect on radiographic detectors and systems.

The neutron radiographic studies are made primarily with a thermal neutron radiographic facility at the NBS research reactor. Work has been carried out with a 3 MeV Van de Graaff accelerator and a 100 MeV linear accelerator. A recommended practice for thermal neutron radiography is being developed in collaboration with the American Society for Testing and Materials. Standards for characterizing neutron beams for radiography and gaging are under investigation. NBS scientists have investigated the use of three-dimensional thermal neutron radiography and have shown the application of this inspection procedure to nuclear fuel subassemblies, batteries, and art objects. Recent work for the U.S. Navy concerns an evaluation of practical neutron sources for neutron radiography.

Electromagnetic Methods

° Visual. NBS scientists are examining methods for the measurement of visual acuity under typical NDE inspection conditions. This includes the effects of subdued lighting common in radiographic reading rooms and of the dark booth situations typically used in fluorescent penetrant and magnetic particle inspection.

The program will characterize test methods used in NDE where the human eye is an integral part of the system. Visual parameters critical to the ability of people to detect and judge visual indications of defects will be identified. These accomplishments will lead to recommendations for improved visual acuity measurement methods.

° Optical. Optical methods utilizing reflected and scattered light are being investigated for the characterization of surface defects and for the measurement of surface roughness. A review of optical NDE methods is in preparation. Consideration is being given to the need for standards in holographic NDE.

° Electrical, Eddy-Currents. Facilities for dc and ac electrical conductivity measurements have been completed as the first stage of a new program in electrical and eddy-current methods. Procedures have been established for the measurement of conductivity over the range of 1-100 percent of the International Annealed Copper Standard. Methods for the calibration of eddy-current test equipment are under investigation.

° Magnetic Methods. This program is particularly concerned with improving measurements for magnetic particle testing. The work includes efforts to determine the uniformity of magnetization within the inspected part and measurements of magnetic leakage flux.

° Microwave Methods. Microwave measurements are being used to determine physical properties of materials. The NDE Program utilizes microwaves to measure moisture content of concrete. These measurements relate to the strength of the material. This represents one area in which NDE methods are being explored for applications in the building industry. Future work to measure moisture content of other building materials is planned.

Penetrant Testing

NBS scientists are investigating the feasibility of preparing a master crack calibration plate for the evaluation of penetrant sensitivity. Electroforming methods are being used for the preparation of well-characterized, reproducible, inexpensive crack plates. The fluids and particles used for penetrant testing are also of interest. Brightness measurements of fluorescent penetrants are planned, along with work on measurements of key properties of the fluids.

Wear Debris Analysis

Detection of worn metal in lubricants in mechanical machinery is now used in both military and civilian programs to determine the proper time for engine, bearing, and transmission overhaul. This method is now being expanded in a current NBS program, partially funded by the U.S. Navy, in which the wear debris particles in the lubricant are detected, sized, and examined in order to determine where and by what mechanism wear is occurring. Magnetic methods for obtaining size distributions of wear particles are used. X-ray microanalysis techniques have been developed for particles in the micrometer range. The techniques offer increased sensitivity for engine condition monitoring compared to conventional SOAP methods.

Thermal-Infrared

A recently completed program resulted in the development of a method for the nondestructive evaluation of batteries used in critical assemblies such as cardiac pacemakers. A microcalorimeter capable of measurements in the 0.2 to 1000 microwatt range is used to measure heat generated in batteries and, in some cases, pacemakers under a variety of conditions. Heat generation by new and partially discharged batteries is measured under no-load conditions as a measure of self-discharge. The work has resulted in a nondestructive method to determine power cell quality. Additional work on infrared NDE systems is being considered.

RECENT PROGRESS IN NDE

This section is devoted to technical descriptions of the progress achieved during the past year in selected areas of the NDE program. Before presenting these descriptions, however, it may be well to briefly discuss a few items that have particular significance from a program planning standpoint.

An assessment of ultrasonic NDE standards in terms of present and future needs was recently completed (see Section BB). This is an important development because it lays out future directions for ultrasonic standards development; directions that NBS and other organizations can follow to improve the reproducibility and quantitative aspects of ultrasonic NDE. In addition, the approach which was taken may offer a model for NBS to follow in assessing standards needs relative to other NDE methods; this direction is presently under consideration.

Another important item concerns a new NBS thrust into optical NDE. Our new projects on light scattering and optical measurement of surface roughness are described in Sections M and N, to follow. There are additional optical projects. One is concerned with a review and assessment of standards needs for holographic interferometry. The review is presently under way with the assistance of Professor Charles Vest of the University of Michigan. A second project on laser techniques in NDE is also planned. The first phase, a literature review, is well along; the work is being done in collaboration with Johns Hopkins University.

A third important development is concerned with a metals characterization project that NBS is pursuing for the National Aeronautics and Space Administration (NASA). The problem concerns improperly quenched aluminum alloy plate; areas in these plates (thickness range about 2.5 to 15 cm) exhibit degraded mechanical properties. These soft areas exhibit lower hardness and changed conductivity values; these methods, therefore, represent the main tools being used to sort aluminum plate material now in the aerospace plants and vehicles. NBS involvement in this important problem presents an opportunity to expand our capability in NDE materials characterization. We are now pursing these opportunities in materials characterization; methods involved include hardness measurement, eddy current conductivity and ultrasonic attenuation and velocity.

Several of the progress reports which follow contain information which was developed without formal support by the NDE program; these are included as part of the total NBS effort because of the NDE orientation of the material.

A. Standards for Ultrasonic NDE

D. G. Eitzen
Mechanical Processes Division
Center for Mechanical Engineering and Process Technology

The detection and evaluation of defects using acoustic emission and pulse/echo ultrasonics relies heavily on comparative measurements. While these techniques have great potential, they are sensitive to measurement system characteristics and to the condition of the reference artifacts used. An effort to improve the reliability and uncertainty of these techniques is underway. Part of this effort has focused on the development of measurement services for transducers and reference blocks. The measurement services now available along with improvements, extensions and applications are listed below:

1. Ultrasonic Transducer Power Output Versus Frequency

The absolute total power output of ultrasonic transducers is measured versus frequency over any part of a range from about 1-20 MHz by means of a modified radiation pressure technique. The uncertainty is frequency dependent but is nominally about ± 5%. In addition to its use in the calibration of ultrasonic transducers for users, the system forms part of the basis for traceability between the Food and Drug Administration and NBS ultrasonic power standards. This is important for determining compliance of many ultrasonic products to FDA promulgated regulations. Work has been done on improving the vibration isolation of the radiation apparatus. Although the present mounts have a very good isolation factor (about 50) at the working frequency of the apparatus, a new, inertial mounting system has been designed and is under construction and should improve the isolation even further.

2. Ultrasonic Transducer and System Power Output by Calorimetry

The time-averaged total absolute power output of a transducer or system is measured by an ultrasonic calorimetric comparator for any voltage input waveform in the range of 1-15 MHz. The uncertainty is approximately ± 7%.

3. Ultrasonic Reference Block Calibration

Sets of ASTM flat-bottomed hole-type ultrasonic reference blocks are compared with an interim reference block and associated model using a well-characterized measurement system. The service provides a mechanism for comparing sets of blocks through the NBS ultrasonic system. In addition to the existing calibration service for aluminum reference blocks, a service for the calibration of steel reference blocks has been established. Also, a more meaningful uncertainty statement has been developed based on a thorough statistical analysis (with the help of the Statistical Engineering Division) of the ultrasonic measurements of reference blocks.

4. By arrangement, carefully characterized ultrasonic source transducers and aluminum reference blocks can be made available for loan. These can provide on-site calibration with the user's system. Using the accurately measured ultrasonic source transducers, a user's power or frequency measurement system can be calibrated in-situ. Four of these source transducers are currently being used in an international intercomparison of ultrasonic power measurement methods piloted by NBS. So far, measurements have been made by six laboratories in four countries. The loaner aluminum ultrasonic reference blocks, which have been carefully compared with the NBS interim reference standards, provide a means for users to compare their reference artifacts with those of NBS on their own ultrasonic systems. These loaner blocks have been used to help establish the basis for a measurement assurance program. An intercomparison on aluminum reference blocks using the loaner blocks as transfer standards and an NBS-developed measurement protocol has been completed to this end. Agreement within 3% has been achieved between NBS and the participating laboratory. This agreement is a factor of 4 better than the existing ASTM method.

Additional work on ultrasonic measurement systems is in progress. A technique for visualizing transducer beam profiles has been developed and disseminated (Materials Evaluation, in press). The technique was developed in response to a need for methods of transducer evaluation suitable for use by the user community. The technique can also be used as a modified C-scan for the inspection of material or parts to display a three-dimensional plot of defects versus position. Work on improved ultrasonic reference blocks has also continued.

B. Pulse-Echo Instrumentation Study

N. V. Frederick
Electromagnetic Technology Division
Center for Electronics and Electrical Engineering

Undesirable, sometimes unacceptable, uncertainties arise in pulse-echo measurements when operators are changed or when an operator repeats a measurement. Attempting to reduce these uncertainties, ASTM Committee E7 is preparing a document for calibrating ultrasonic pulse-echo equipment.

At NBS, through measurements on standard metal blocks, we are evaluating the ASTM E317 calibration document. To date, our studies have suggested two innovations: a simple, inexpensive standard test specimen and a transducer-probe modification.

The prototype standard test specimen consists of a right-circular-cylinder brass block with lathe-finished ends. Identical gold-plated quartz piezoelectric transducers are attached to each end with low-melting-point solder (Rose's alloy). Test-range requirements determine specimen length. A simple, rugged metal box with permanently attached connectors houses the specimen. Use of this specimen permits the operator to reproducibly evaluate several parameters: horizontal linearity for short, medium, and long ranges; vertical linearity; receiver signal-to-noise ratio; receiver-gain stability; and pulser performance. NBS will recommend that the Committee request manufacturers to supply such a standard specimen, or a set of them, as an integral part of each piece of test equipment. This standard specimen will provide a means for maintaining an operator-bias-free record of equipment performance.

A slight modification of existing transducer-probe design has practically eliminated the gross echo-pattern variations that arise from irreproducible transducer-specimen coupling. The modification also permits rapid, unambiguous evaluation of various couplants. The modification consists simply of attaching three small feet to the transducer housing. With a small pressure, these feet act as spacers between the transducer and specimen surfaces, uniformly fixing the couplant layer thickness. The feet do not (must not) contact the transducer itself. The only trade-off for cleaner, more stable, more reproducible echo patterns is a slight attenuation due to a thicker couplant layer. For the feet, a prototype design used metal shim-stock chips typically 0.8 mm x 1.0 mm x 0.1 mm thick, their surface area being approximately one percent of the transducer-housing surface area. A pressure-sensitive cyanoacrylate cement holds the spacers on the housing.

C. Ultrasonic Diffraction Technique for Characterization of Fatigue Cracks

S. Golan
Office of Nondestructive Evaluation
National Measurement Laboratory

A technique for the sizing and characterization of cracks with ultrasonic diffracted waves has been developed.

When an ultrasonic wave impinges on the tip of a crack, waves of the shear and compression modes are diffracted in a circular form. From measurements of the arrival time of the diffracted ultrasonic wave the depth of the crack tip can be computed by applying a single or double transducer technique (see Figure 2), provided the tip-diffracted signal can be detected. This technique involves time measurements only; therefore, sizing of cracks can be performed with high accuracy.

The amplitude of a diffracted wave is comparatively low, approaching noise level; therefore, reliable results can be obtained only if optimum conditions are established, and if the tip-diffraction signal can be identified unambiguously in the noisy background. Various parameters influencing the quality of the test, such as angle, mode, wedge efficiency, double or single transducer technique, etc. have been investigated in order to determine optimum testing conditions, and a technique was developed to identify the signal from its response to dynamic loading.

The technique was used to characterize fatigue cracks (in collaboration with Oak Ridge National Laboratory and the University of Tennessee). Very good correlation between ultrasonic and direct measurements were found (see Figure 3) and other important characteristics such as crack closure and crack surface topography were evaluated.

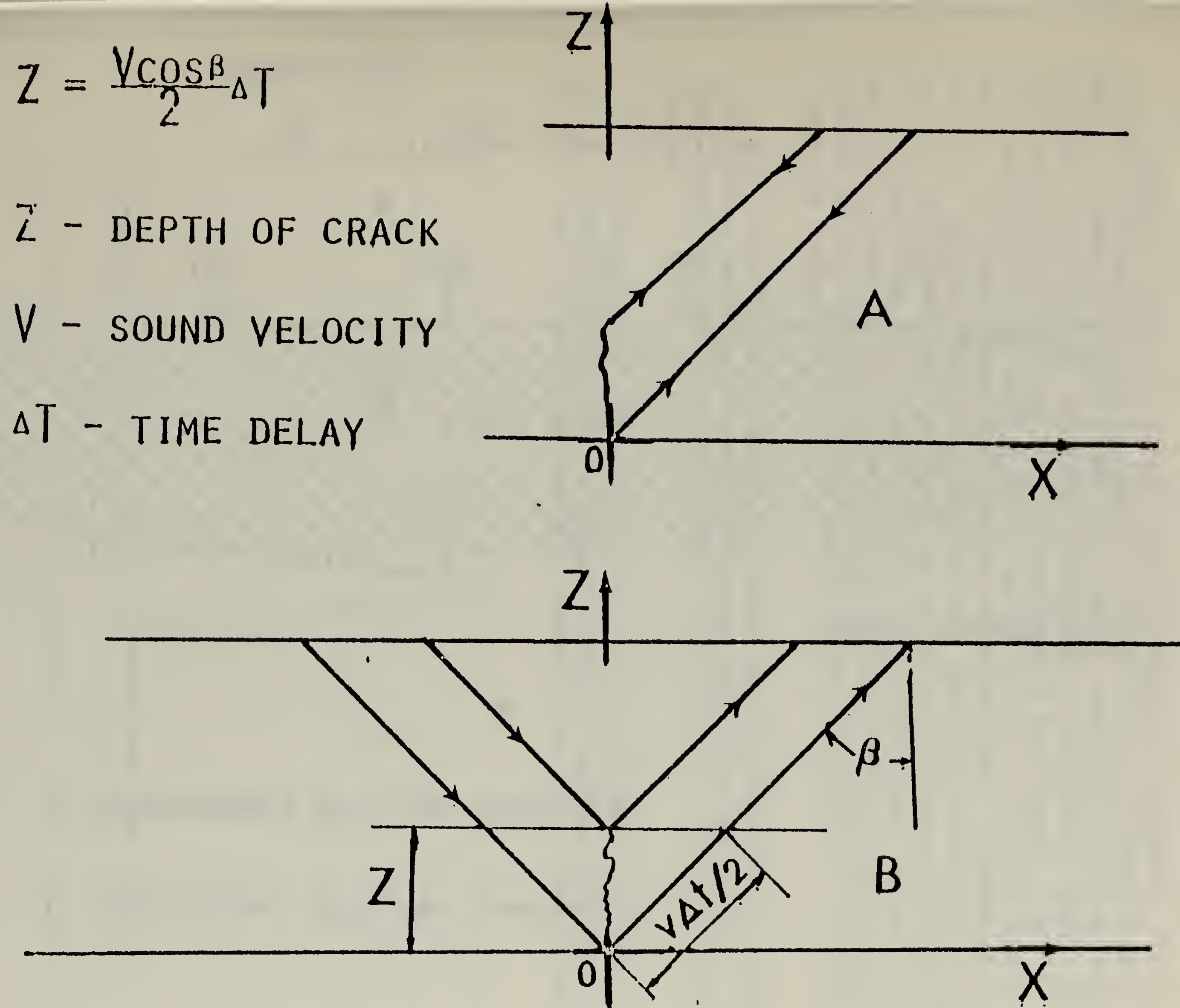

Fig. 2. Sizing of cracks with tip diffracted waves (A) single transducer technique (B) double transducer technique.

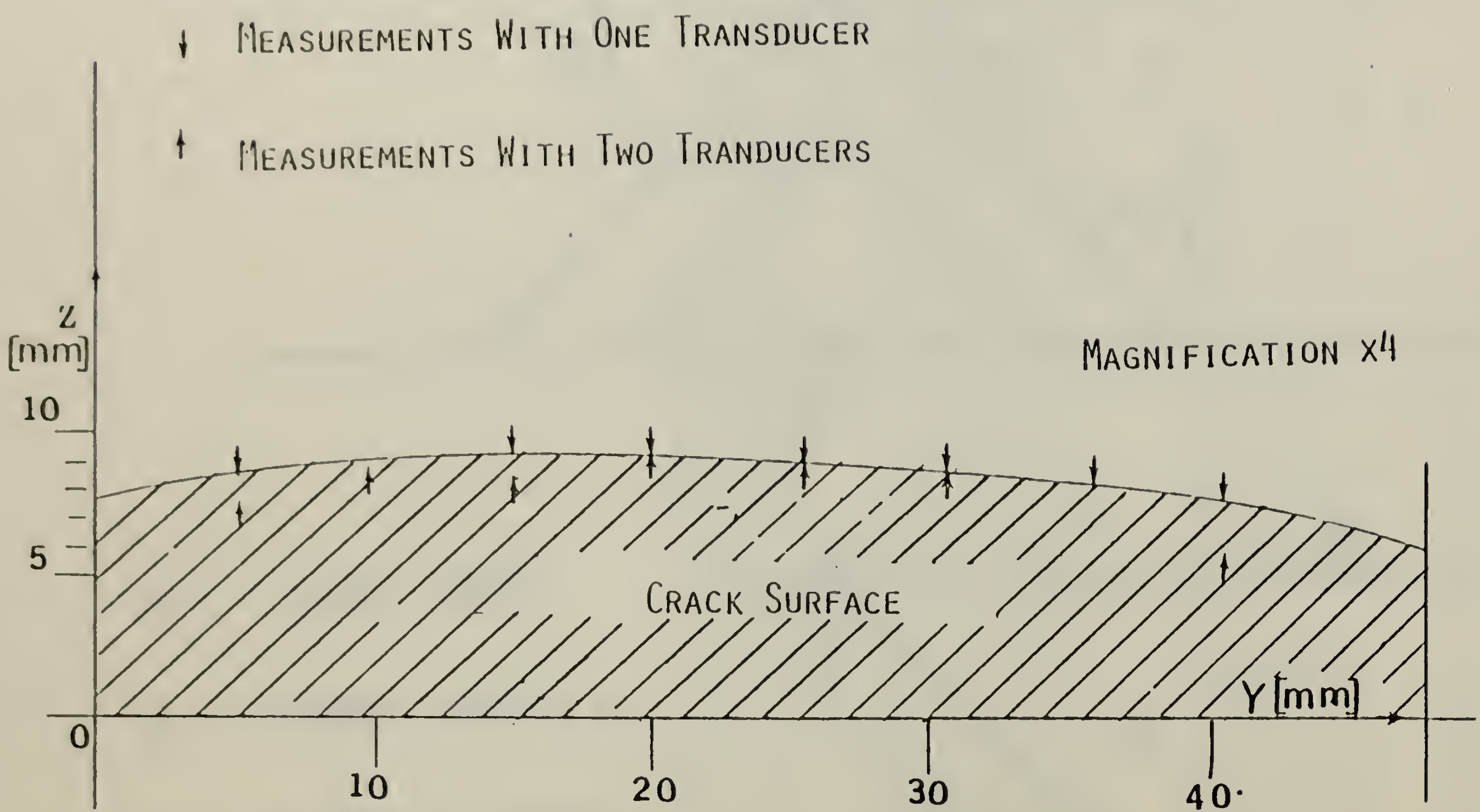

Fig. 3. Ultrasonic crack profiling.

D. Ultrasonic Imaging

M. Linzer
Signal Processing and Imaging Group
Center for Materials Science

Several studies to establish the theoretical framework for advanced, computer-based, ultrasonic imaging systems have been completed. This work has been directed, primarily, toward convolution/backprojection methods for producing ultrahigh-resolution reflectivity images through the use of enclosing and partially-enclosing apertures. Circular arrays for two-dimensional imaging and spherical as well as hemispherical arrays for three-dimensional imaging were analyzed. Narrowband, wide-band and optimum transmit waveforms were considered and detailed computer simulations were generated for a variety of potential experimental situations. See for example, Figure 4. A preliminary investigation was made of approaches for correcting velocity, attenuation and reflectivity images for ray refraction and of algorithms for frequency-dependent time-gain compensation.

These studies are expected to guide the development of systems that can provide images with greatly improved resolution and accuracy. This development activity has begun with construction of a motor-controlled scanner.

In related work, the sensitivity of our dynamically-focused annular array system (described in last year's report) was improved by more than 20 dB. The system was successfully demonstrated in a clinical environment.

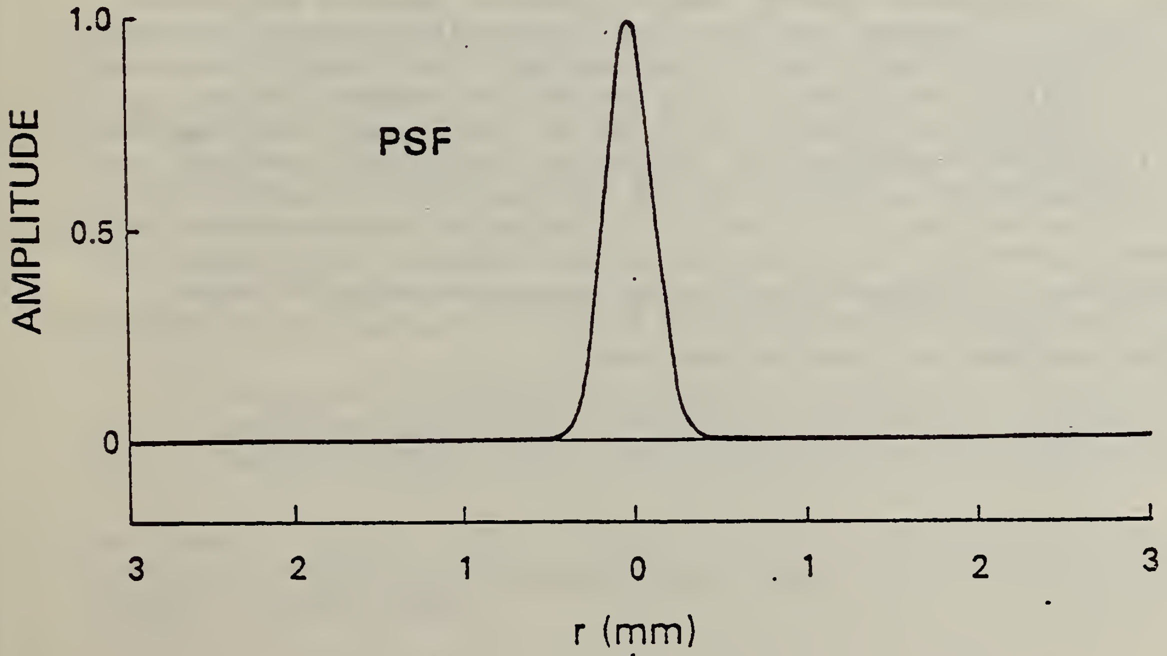

Fig. 4. Simulated point-spread function for computer imaging using a spherical array and an optimum pulse having a width of 0.4 mm at half amplitude. Note the absence of sidelobes.

E. Acoustic Emission

N. Hsu
Mechanical Processes Division
Center for Mechanical Engineering
and Process Technology

An acoustic emission (AE) detection system, be it a simple single channel system or a multi-channel computer-based system, requires a simulated AE source for checking general system performance and for setting amplifier gains and threshold levels. Commonly used simulation techniques such as pulsed piezoelectric transmitters, sparks, and helium gas jets have the disadvantages that their signatures have never been precisely determined and that the control of these simulated sources is rather difficult and arbitrary.

The concept of using a breaking pencil to generate a simulated AE was first reported by this author more than three years ago. Since then it has received wide acceptance as a simple and effective field system calibration device. In the past year the device has been further refined in that independent and direct measurement of the peak breaking force is made with a static force load cell incorporated in the construction of the device. Consequently, an AE system can be calibrated with a physically known quantity as the input source. A report is being prepared which provides details of the design and test results of correlation studies between the monitored input force measurement and various empirical AE parameters. The device is now expected to see even wider use and should contribute substantially to the standardization of the present generation of AE detection/processing systems.

Also, a systematic study of the problems and possible solutions associated with AE source location using triangulation methods has been initiated during the past year. The objective of the study is to devise system calibration techniques to make the methods reproducible and reliable. A detailed error analysis of some of the source location computation algorithms has defined the limitation of specific algorithms and sensor configurations. Included in the study are the characterization of the various modules of a triangulation system and the development of laboratory experiments and theory to analyze transient wave propagation in structures. The system characterization and the transient wave analysis are essentially an extension of the study of a well-characterized AE system developed and reported previously.

F. Nondestructive Evaluation of Composites

H. M. Ledbetter, J. C. Moulder, and S. K. Datta*
Fracture and Deformation Division
Center for Materials Science

Ultrasonic waves provide a powerful nondestructive tool for studying a solid's general mechanical state. Well-known solid-state ultrasonic applications include determinations of thickness, residual stress, elastic properties, texture, and phase transitions. Variously polarized ultrasonic velocities provide such information. Wave-scattering measurements furnish information on the location, size, and geometry of flaws. Wave-attenuation measurements yield information on internal friction (absorption) and scattering (inhomogeneities). All internal defects, even phonons, interact with elastic waves and attenuate them. Attenuation applications include determinations of defect types, defect density, and grain or particle size. For isotropic homogeneous materials the theory and practice of ultrasonic velocities in solids is reasonably advanced.

Composites--being by nature inhomogeneous, anisotropic, densely flawed, and residually stressed--provide attractive media for theoretical, experimental, and applied ultrasonic-wave studies. Partially offsetting this attractiveness, exact theories and measurements on composites are precluded by the uncertainty and complexity of the distribution of the reinforcing particles or fibers. Besides the properties of the constituent fibers and of the matrix, it is this distribution function that determines the composite's macroscopic properties.

We propose to study, both experimentally and theoretically, elastic waves in a single composite--boron-aluminum--to understand its macroscopic anisotropic elastic-constant and internal-friction properties. Despite obvious needs for such basic comprehensive studies, none have been reported to date. Thus, an opportunity exists for applying fundamental theory and measurement techniques to strengthen our understanding of elastic waves in composites and to provide a firmer base for nondestructive-evaluation technology.

Our specific current research goals include combined experimental and theoretical studies:

1. Determine orientational dependence of ultrasonic velocity for both longitudinal and transverse polarizations. Develop the velocity tensor. Use a MHz-frequency pulse-echo technique.

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2. Combine these results with mass density to develop the C_{ij} elastic stiffness tensor.

3. Similar to 1 and 2, using a kHz-frequency technique, develop velocity tensor and S_{ij} elastic-compliance tensor.

4. Examine 1 and 3 results for dispersion. If discovered, try to explain.

5. Model the anisotropic macroscopic elastic properties such as Young's modulus, shear modulus, bulk modulus, compressibility, and Poisson's ratio in terms of constituent elastic properties.

6. Develop graphical representation surfaces for all the elastic constants listed in 5 and for the sound velocities.

7. Measure attenuation and damping as a function of orientation using both pulse-echo and resonance methods. Develop representation surfaces for internal friction.

8. Determine anisotropy of Rayleigh-wave velocity in laminae plane. Launch waves by laser excitation. Detect by laser-beam deflection, a technique to be developed in our laboratory.

Items 1 through 4 are complete, and items 5 and 6 are underway.

To a very good approximation, the boron-aluminum composite can be represented by five independent elastic constants: $C_{11} = C_{22}$, C_{33}, $C_{44} = C_{55}$, C_{66}, and $\nu_{31} = \nu_{32}$. The remaining elastic constants are computed from the relationship: $C_{12} = C_{11}-2C_{66}$ and $C_{13} = C_{23} = \nu_{31}\ (C_{11}+C_{12})$. Using theories due to Hashin and Rosen (1964) and Bose and Mal (1973, 1974), we find excellent agreement between constituent and composite elastic constants. In these latter two papers the authors consider (for a random fiber distribution) the in-plane problem of waves moving perpendicular to the fibers and also the antiplane-strain problem of a wave polarized along the fiber direction but moving in a transverse direction.

The five independent elastic constants were determined by measuring eighteen differently polarized wave velocities along [100]-type and [110]-type directions, [001] being the fiber direction. Agreement within a few percent was achieved, both in internal consistency and in terms of microscopic-macroscopic models mentioned above. These results may represent state-of-the-art measurements on metal-matrix composites. They were obtained with a custom pulse-echo system featuring narrow pulses, wide bandwidth, a simple impedance-transforming amplifier, and an FET transmission gate.

G. Polymer Sensors for NDE of Bearings

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The NDE work of the Bulk Properties group emphasized a comparison of the usefulness of polymer sensors and conventional accelerometers for monitoring the condition of bearings (see publication in the Proceedings of the 28th Meeting of the Mechanical Failures Prevention Group, NBS Special Publication 547, pp. 303-314, July 1979).

In the study a horizontal shaft supported on ball-bearings was used; a quiet bearing was at one end and a noisy bearing at the other. An isolated electric motor was coupled to the shaft by a flexible belt so that only the bearings contributed measurable noise to the structure supporting the shaft. A polymer sensor was fixed to the stationary race of each bearing and a miniature piezoelectric accelerometer was mounted on the supporting structure as close to each bearing as practicable.

It was found that polymer sensors have several advantages. The principal advantage derives from the flexibility and low density that allow the polymer sensor to be mounted directly to the bearing. So mounted, it responds only to the bearing noises. Conventional accelerometers are relatively massive and require specially prepared mounting surfaces of appreciable area. These characteristics require them to be mounted some distance from the bearing where they can be affected by noise from other sources. This extraneous noise can cause uncertainty as to which of several bearings is bad.

It has been suggested that polymer sensors could provide a non-invasive means of detecting cracks of the kind recently affecting DC-10 airplanes. A polymer gage cemented to a metal surface responds to surface strain in all directions and detects a signal which can be analyzed into a spectrum of resonances of the metal panel. A change in the structure of the metal preliminary to cracking (and certainly, development of a crack) will cause a significant shift in resonance frequencies and amplitudes. Polymer sensors are cheap so that one can be attached to each critical surface. The sensor and lead constitute a continuous thin sheet of polymer that would not affect the behavior of the panel. All resonances of the panel would be excited any time the engines were operating. Before each take-off, a superposition of the current spectrum on a spectrum recorded when the plane was known to be in good shape would detect any change in the integrity of the panel.

Other proposed NDE work consists of the use of polymer sensors to detect broken strands in airplane control cables and the use of polymer sensors in a nonresonant method to measure the real and imaginary parts of the elastic moduli of long, thin rods as continuous functions of frequency and static load.

H. Electrochemical Noise

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The detection and analysis of small amplitude fluctuations of the current and/or potential of galvanic cells can give some information concerning the processes occurring at the electrodes. The measurement of electrochemical noise is being investigated as a means to detect the onset of localized corrosion.

For the purpose of studying corrosion processes, it is often convenient to control the potential of the electrode under study. This is accomplished by means of a potentiostat. Commercial instruments, however, tend to introduce unacceptable noise levels in the circuits, preventing the study of the signals of interest. For this reason, a special low-noise potentiostat was developed at NBS with the cooperation of the Special Analytical Instrumentation Group, Center for Analytical Chemistry. The instrument is designed for the detections of fluctuations in the frequency range between 0.1 and 2000 Hz. The internal noise is of the order of $3 \cdot 10^{-8} V/\sqrt{Hz}$. Figure 5 shows the noise current produced by the potentiostat on different resistive loads. It can be seen that current fluctuations in the nA range caused by changes in the electrode characteristics can be detected above the instrumental noise.

Noise measurements are now being made on various electrodes. For aluminum in neutral solution, for instance, pitting is correlated with a large increase of the noise current, as shown in Figure 6. When the electrode potential is brought above the pitting potential (about -650 mV vs SCE), the noise current increases by almost three orders of magnitude below 100 Hz.

Other electrode systems are being studied in order to assess the sensitivity and range of application of this novel tool for the study of corrosion.

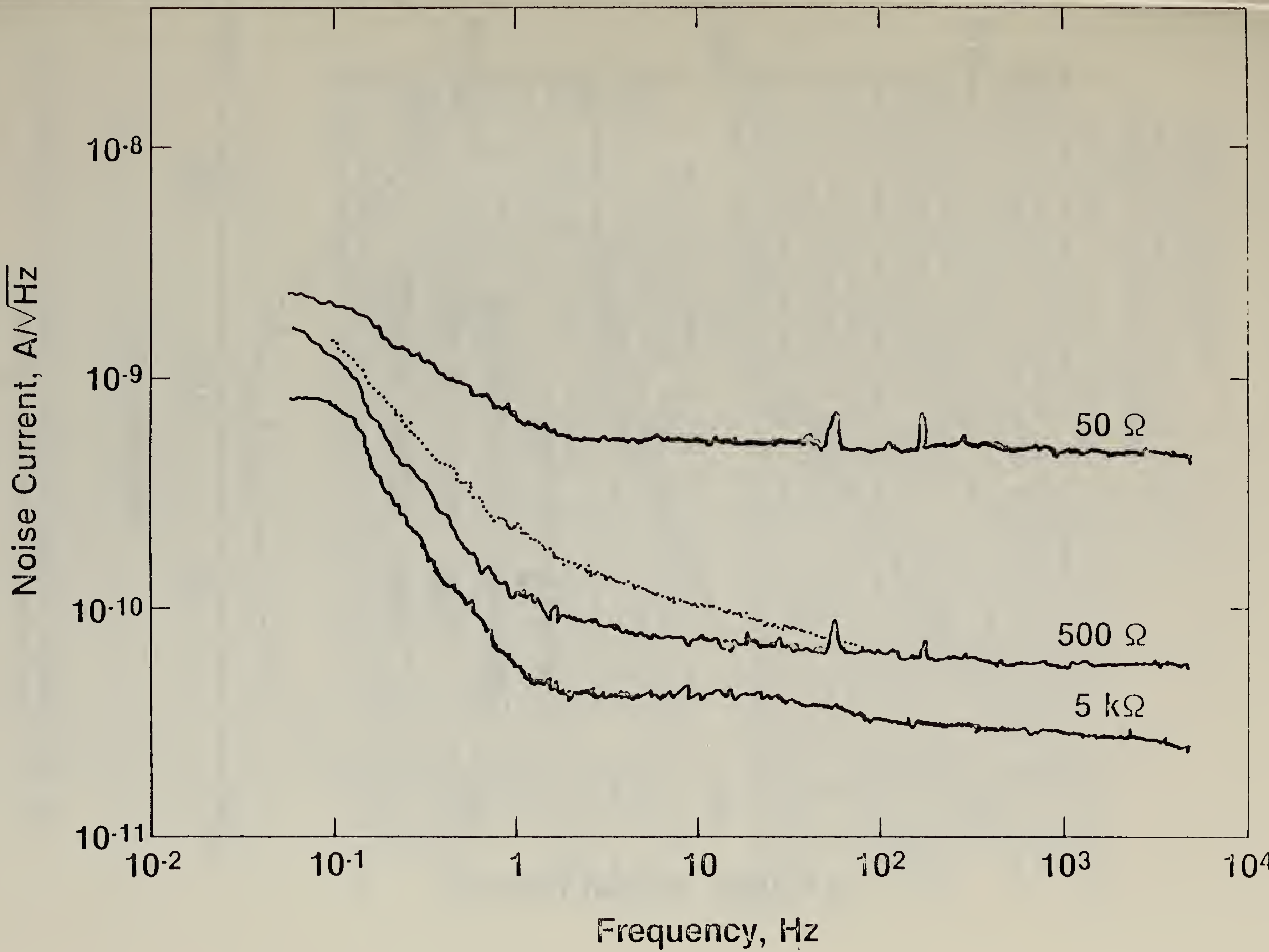

Fig. 5. Noise current produced by the potentiostat on different resistive loads.

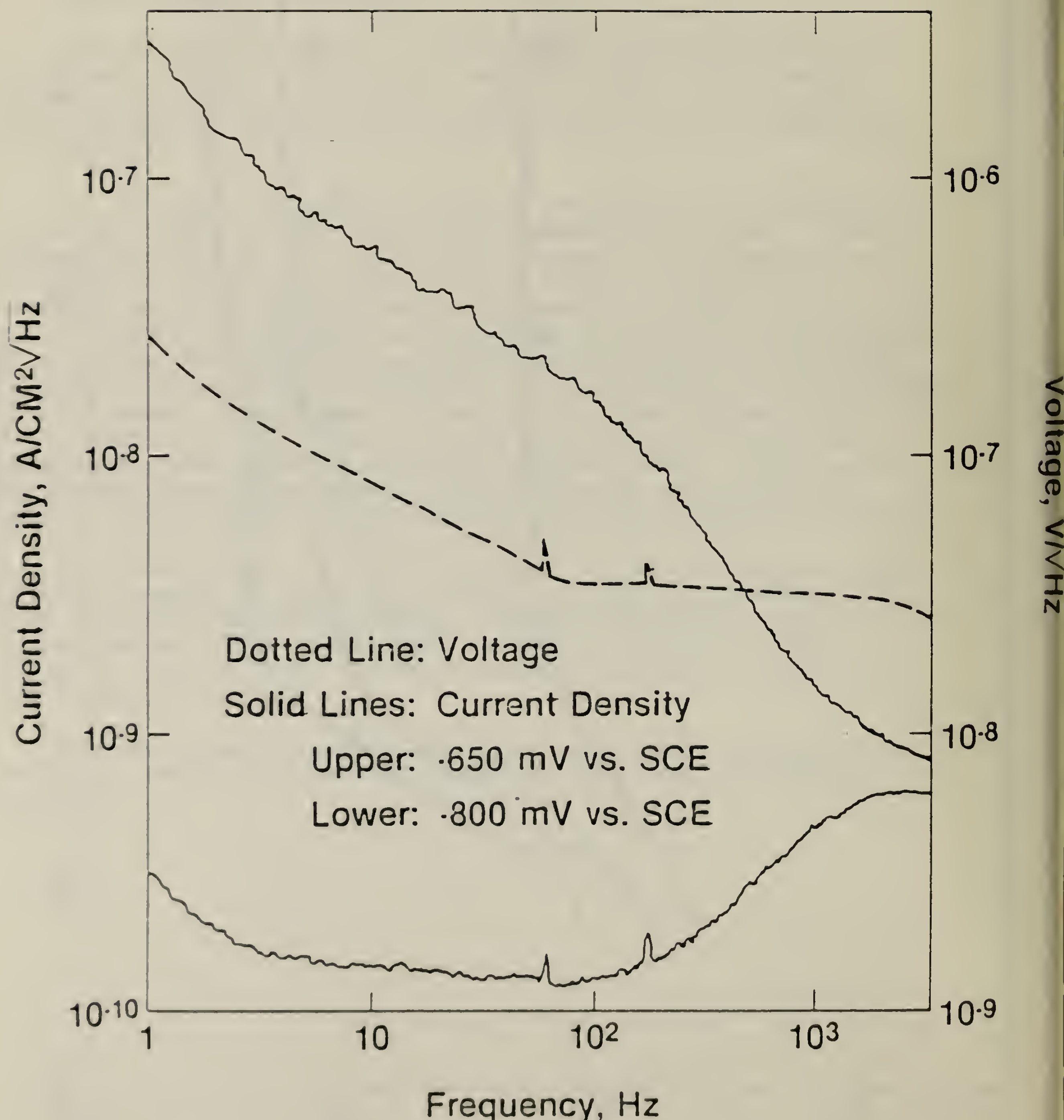

Fig. 6. Aluminum in neutral solution; pitting is correlated with a large increase of the noise current.

I. Magnetic Measurements

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Center for Materials Science

The magnetic particle method is a relatively simple and inexpensive, yet effective and rapid method; it is currently in wide use for both production and field testing of ferromagnetic components. Despite its apparent simplicity, a large number of variables influence the process and need careful control in order to obtain repeatable and reliable results. To aid in this control, use of a test ring with artificial subsurface defects is often specified. The extent to which such a test ring evaluates the properties of the particle being used rather than a combination of operator skill, proper particle densities, proper magnetization levels and other contributing factors, is poorly understood. An evaluation of the importance of the various contributing factors requires the development of a mathematical model to describe the formation of magnetic particle indications. To this end, the development of indications on the test ring currently specified in MIL-E-6868E (and proposed for inclusion in the ASTM magnetic particle recommended practice) is under investigation.

In developing a model to describe indication formation on a test ring, a description of the leakage field from the artificial defects is required. Because of the non-linearity of a ferromagnetic material such a description poses formidable mathematical difficulties. However, we have shown experimentally that, to a good approximation, a simple linear dipole model can be used to describe the leakage field from cylindrical defects provided that a proper equivalent depth, which is less than the true depth, is used. A calculated leakage field is illustrated in Figure 7. Measured and calculated fields are compared in Figure 8. Using the observed leakage field strengths and the known number of defects that form indications on the test ring at various current levels, a detection criterion has been suggested in terms of the force experienced by an isolated spherical particle. An extension of this criterion to other situations would be very useful and might allow the calculation of required magnetization levels and detectable defect size, parameters which must now be determined empirically.

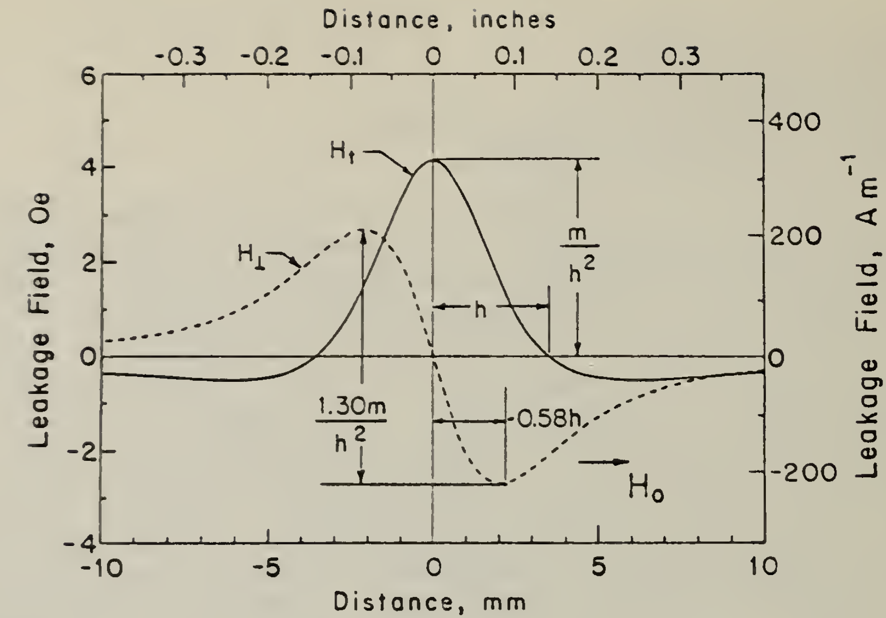

Fig. 7. Calculated components of the magnetic leakage field at the surface from a subsurface cylindrical defect in a linear isotropic magnetic medium of high permeability. m refers to the dipole moment per unit length of the defect an h to the height above the center of the defect.

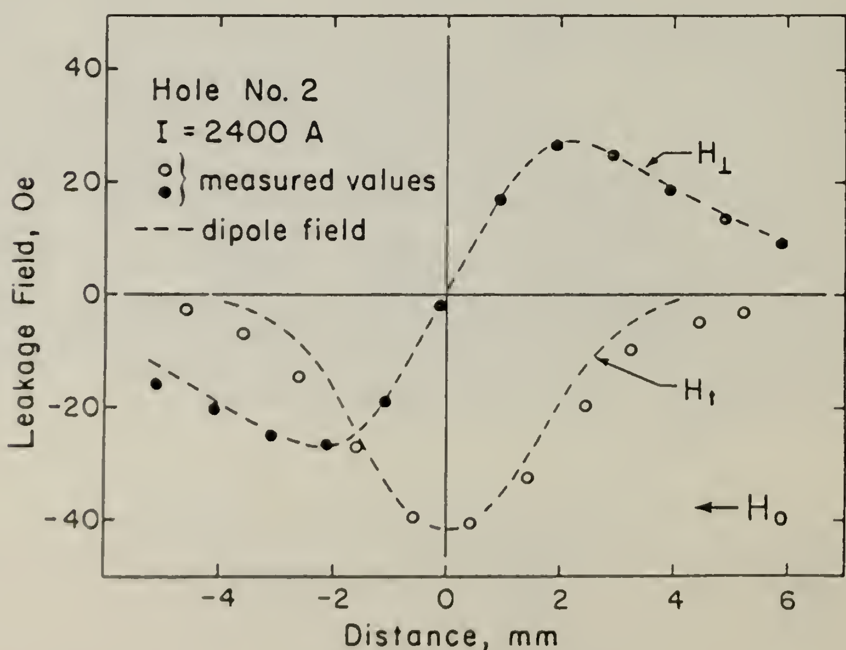

Fig. 8. Experimental transverse, H_t, and perpendicular, $H_\perp$, leakage fields for hole number 2 of the test ring specified in MIL-E-6868E with an applied magnetizing current of 2400 amps. The dotted lines are calculated for a dipole with an m of 607 Oe mm^2 and an h of 2.6 mm.

J. Eddy Current Conductivity Measurements

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The objectives of this project are (1) to develop a calibration service for electrical conductivity standards in the range 10% - 100% IACS and (2) to produce electrical conductivity standards which would become NBS Standard Reference Materials (SRMs), in a joint effort with the Metal Science and Standards Division.

The calibration service project can be divided into three distinct areas in which work has been done: (1) the development of a DC measurement system to measure resistance at the microohm level, (2) the design and construction of an eddy current bridge to test primary standards for uniformity and to compare test samples with the primary standards and (3) the development of primary conductivity standards.

The DC measurement system has been completed and tested on several test bars. The stability and sensitivity of the system is within the requirements of measuring at the microohm level. The total accuracy and precision of the system is not as yet known due to the lack of a uniform sample needed to determine these quantities.

An eddy current bridge has been developed which is based on a new concept in eddy current measurement. A paper discussing the theory, construction and operation of the bridge was presented at the "Symposium on Eddy Current Characterization of Materials and Structures" held at NBS, September 5-7, 1979. The principle of operation is that all measurements are made at a constant skin depth instead of the usual measurements made at a constant frequency. Advantages of the system are that all conductivity measurements can be based on a single standard (usually a minimum of ten standards are needed to cover the range 1-100% IACS) and lift-off is automatically resolved in the system. The bridge circuit is a modified Maxwell bridge with a grounding network. The range of this instrument is .1-10 mH inductance and 2-200 ohms for the series resistance. The instrument works in the frequency range 5 kHz - 100 kHz. Initial testing of the system has shown that the accuracy of the system is .01% of the conductivity being measured.

The eddy current bridge has been used to scan the primary standard bars at different skin depths. From the scans it was determined that only one of the test bars has the uniformity necessary to be used as a primary standard. The use of this one bar will necessitate increasing the NBS total uncertainty because even this bar has areas in which the conductivity varies by approximately 0.1%σ. All NBS bars were heat treated to improve the uniformity of the electrical characteristics but the improvement was not sufficient to qualify the remaining bars as primary standards.

The second objective of the project, the development of electrical conductivity standard reference materials is being done jointly with the Metal Science and Standards Division. This project was initiated during the current fiscal year. Responsibilities for various areas of the project have been defined. It was decided that SRM's in the conductivity range of aluminum alloys would be the first produced. The geometry of the samples has been set. The dimensions of the standards will be 1 1/2" x 1 1/2" x 1/2". The alloys have also been chosen so that the approximate conductivity of the standards will be 20%, 30%, 40% and 50% IACS.

During the next fiscal year more bar samples will be fabricated. The bars will be cut from larger metal plates in an area of the plate that has been determined to have uniform electrical characteristics. More primary standards are necessary to establish NBS measurements and to lower the total uncertainty that will be used in the NBS calibration service.

Development of the NBS eddy current bridge will continue. A voltage follower network will be built and tested to determine if such a network can be used in the grounding network of the bridge. If phase change in the follower can be held to a negligible amount it would replace the grounding network of the present bridge. The voltage follower network would simplify the bridge balance and reduce the time spent in balancing the bridge by approximately half. The ranges of inductance and resistance that can be measured will be increased to provide for the measurement of a wide variety of coils.

The calibration service will be initiated as soon as the primary bars can be machined and calibrated. It is planned that the service would be announced in December, 1979.

Testing of electical conductivity SRM's will start in the spring of 1980. The initial tests will determine the uniformity of these metal blocks. Eddy current tests will be done at different frequencies to determine if surface hardness causes error in eddy current measurements. The magnitude of the error will be determined.

K. Eddy Current Imaging System

B. Field
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The objective of this project is to develop an eddy current flaw detection system with a more meaningful display and to demonstrate the feasibility of such a system for determining the type and shape of flaws. Work on this aspect of the project started with a literature search for papers concerning defect detection or characterization using eddy current techniques. A promising approach for a sensor was reported by McMaster (Met. Eng. Quart., pp. 32-48, May 1966) using a Hall effect detector. A similar sensor was built and several experiments were performed. As a result of these experiments (and later discussions with McMaster) it was learned that pickup of extraneous signals by the leads introduced significant problems. Adequate shielding of the leads proved difficult and appeared to be impractical for a large array of sensors, and thus it was felt that the sensor design could be better met by a differential coil arrangement.

A probe assembly of our own design, consisting of an array of small pickup coils (probably about 50 coils) with four large driving coils arranged in a square around the array of pickup coils has been proposed as a possible flaw detector. The present implementation of this idea is shown in Figure 9, a drawing of a prototype probe assembly; this is placed on the flat surface to be analyzed. Driving coils on opposite sides of the array will be excited simultaneously but with current signals 180 degrees out of phase with each other. By varying the relative signal strength of the two coils, we should be able to detect conductivity discontinuities with high spatial resolution. Information about the shape of the discontinuity can be determined by separately energizing the orthogonal pair of driving coils. This idea, as yet, is untested, but, preliminary experiments indicate that this is a feasible concept. Potential advantages of this concept are:

1) the assembly allows high spatial resolution of discontinuities with a relatively small number of pickup coils.

2) a reasonably large area (approximately 80 sq. cm in the prototype) can by analyzed with no mechanical scanning required.

3) the system will be able to provide limited information about the shape of the discontinuity, e.g., distinguishing between cracks and pits.

4) the test is most sensitive to surface discontinuities, but limited information about sub-surface discontinuities and the depths of discontinuities may be available.

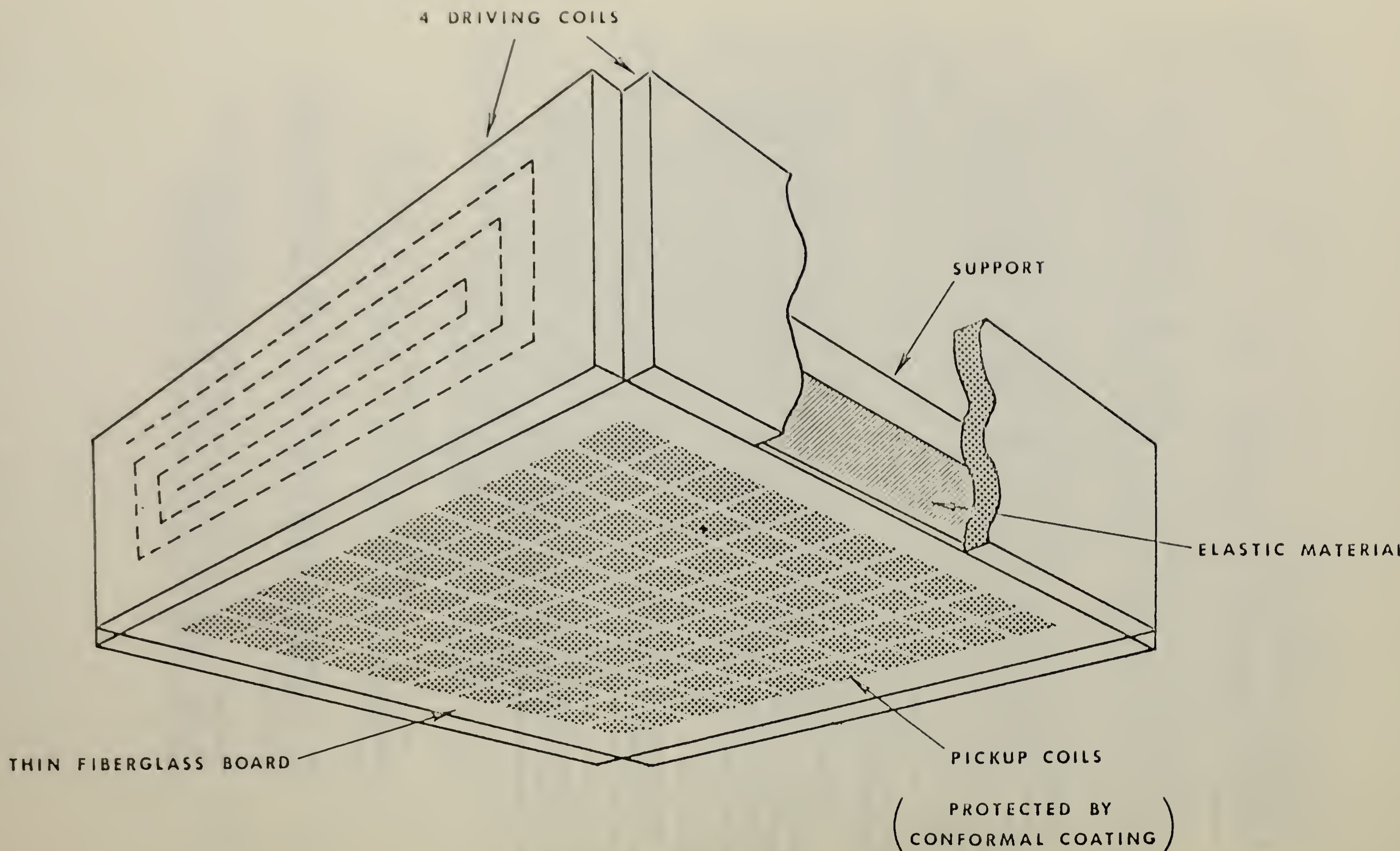

Fig. 9. PROTOTYPE PROBE ASSEMBLY FOR THE EDDY CURRENT IMAGING SYSTEM

5) the prototype probe is designed for flat surfaces, but a modification of the probe will also allow testing of slightly curved surfaces.

A desktop computer will perform experiment control, data logging, and data reduction for the system. The computer has been interfaced successfully with a frequency synthesizer (for energizing the driving coils) and a general purpose interface crate of our own design. The interface crate will allow us to easily interface a variety of instruments to the computer. We have the ability at present to perform data logging of eight analog channels (with 0.025% accuracy) and to control a mechanical scanner. Several computer programs have been written to perform a one-dimensional scan of an aluminum plate, digitize the signals from the pickup coils, and graphically display the results. A lock-in analyzer is used to amplify and phase-detect the in-phase and quadrature components of the pickup coil signals. These mechanical scanning experiments were used as a convenient method for examining eddy current fields to produce an improved design for the pickup coils.

L. Theoretical Modeling in Eddy Current NDE

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Center for Materials Science

We have completed the calculations of the impedance of a coil which contains a conducting cylinder with a long radial surface crack. The calculations were performed by two independent methods. The first method employed an eigenfunction expansion of the magnetic field in the conductor, with the expansion coefficients determined by the fitting of boundary conditions on the surface and in the crack. The second method of calculation was conversion of the problem to an integral equation for the eddy current density on the surface of the conductor. The advantage of the second approach is that it is applicable to any two-dimensional shape of cross section of the conductor; in addition, it offers an independent check on the first method of calculation.

The results of the calculations for the cylinder with a crack are shown in the following figures. The fractional change of the real (resistive) and imaginary (inductive) parts of the impendance are shown plotted against the ratio of crack depth to radius (d/a) for a wide range of values of the ratio of radius to skin depth (a/δ). For the case of a tight crack these calculations represent a complete solution of the problem. Open cracks can be treated as individual cases by the integral equation method.

The results described above are all related to the detection of long flaws in bodies of uniform two-dimensional cross section, such as rods, cylinders and strips. With this accomplishment as a start, we plan to go on to three-dimensional problems which are of greater interest. A possible problem for attack is the configuration in which an eddy current probe is passed above a conducting plane with a crack or other defect on or beneath the surface. Such problems have, in the past, been treated under the approximation that the defect size was small with respect to the skin depth. By extension of the integral equation method we plan to treat such problems more generally.

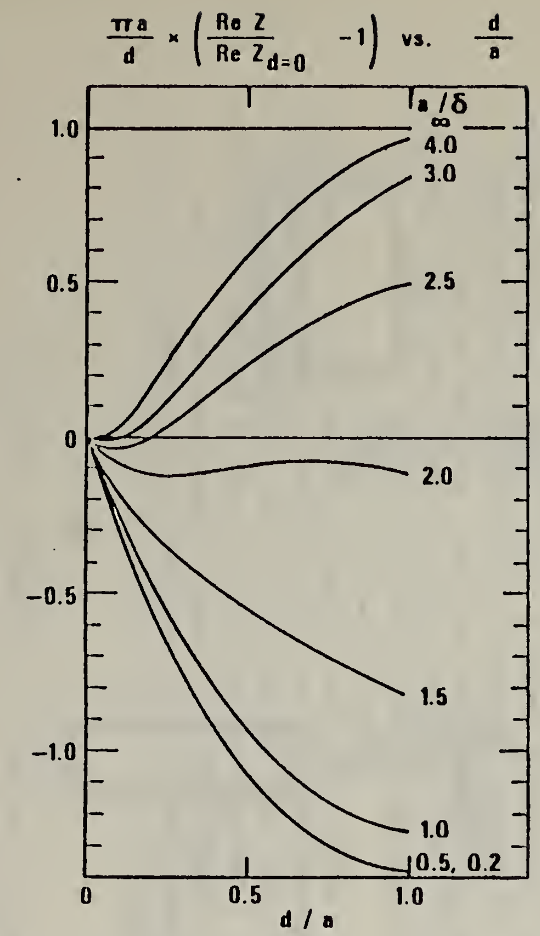

Fig. 10. Fractional change due to the crack of the impedance as a function of d/a for selected values of a/δ.

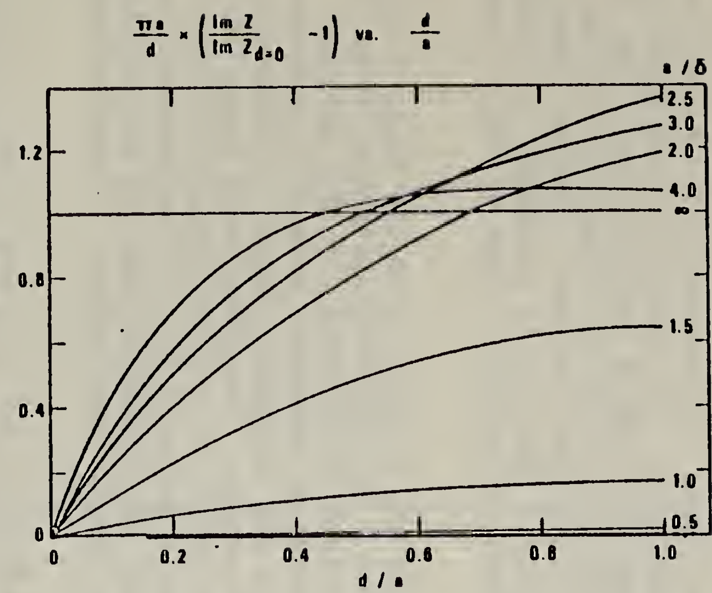

Fig. 11. Fractional change due to the crack of the imaginary part of the impedance as a function of d/a for selected values of a/δ.

M. Optical Nondestructive Evaluation

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The use of optical techniques for nondestructive evaluation of materials is growing in importance. For example, holographic interferometry has become a standard procedure for detecting flaws in tires. Optical scattering techniques are in use for detection of flaws in hypodermic needles and artillery shell casings. Speckle interferometry is being developed as an optical NDE tool to complement holography. It is the purpose of this project to provide a sound scientific basis for optical NDE methods.

At present, the focus of our program is on the study of light scattering from surface flaws. A scattering apparatus, shown schematically in Figure 12, has been constructed for this purpose. In preliminary scattering experiments conducted with this apparatus, the beam from a CO_2 laser source was propagated normal to the surface of a brass specimen containing a groove. The groove with dimensions approximately 50μm wide, 50μm deep and 1 cm long was produced by spark erosion. Scattered light within a solid angle of 2×10^{-5} was measured as a function of the angle between the scattered beam and the incident beam in a plane perpendicular to the specimen groove. These measurements define a scattering function.

Representative data for an angular scan are shown in Figure 13. The structure in the scattering function resembles the diffraction pattern of a single slit, which is to be expected by application of Babinet's principle. From the spacing of the minima in the curve and the use of the formula for single slit diffraction, one calculates that the width of the groove should be 52μm, in close agreement with the approximate dimension given above.

An interesting feature in Figure 13 is the double peak to the right that appears near the scattering angle $\theta = \underline{17°}$. This structure appears to be a property of the groove because, when the specimen is rotated 180° about the normal to the specimen surface, the double peak shifts to the left near $\theta = \underline{-17°}$. This suggests that the scattered light contains more detailed information about the groove structure.

In the course of setting up the scattering experiment, it was found that the system alignment was a more critical than initially suspected. For example, if the groove was not normal to the scattering plane but deviated by only 0.3°, the scattering function would become grossly distorted and asymetric. Furthermore, asymmetry was observed in the scattering function when the axis of rotation of the detector did not coincide with the groove.

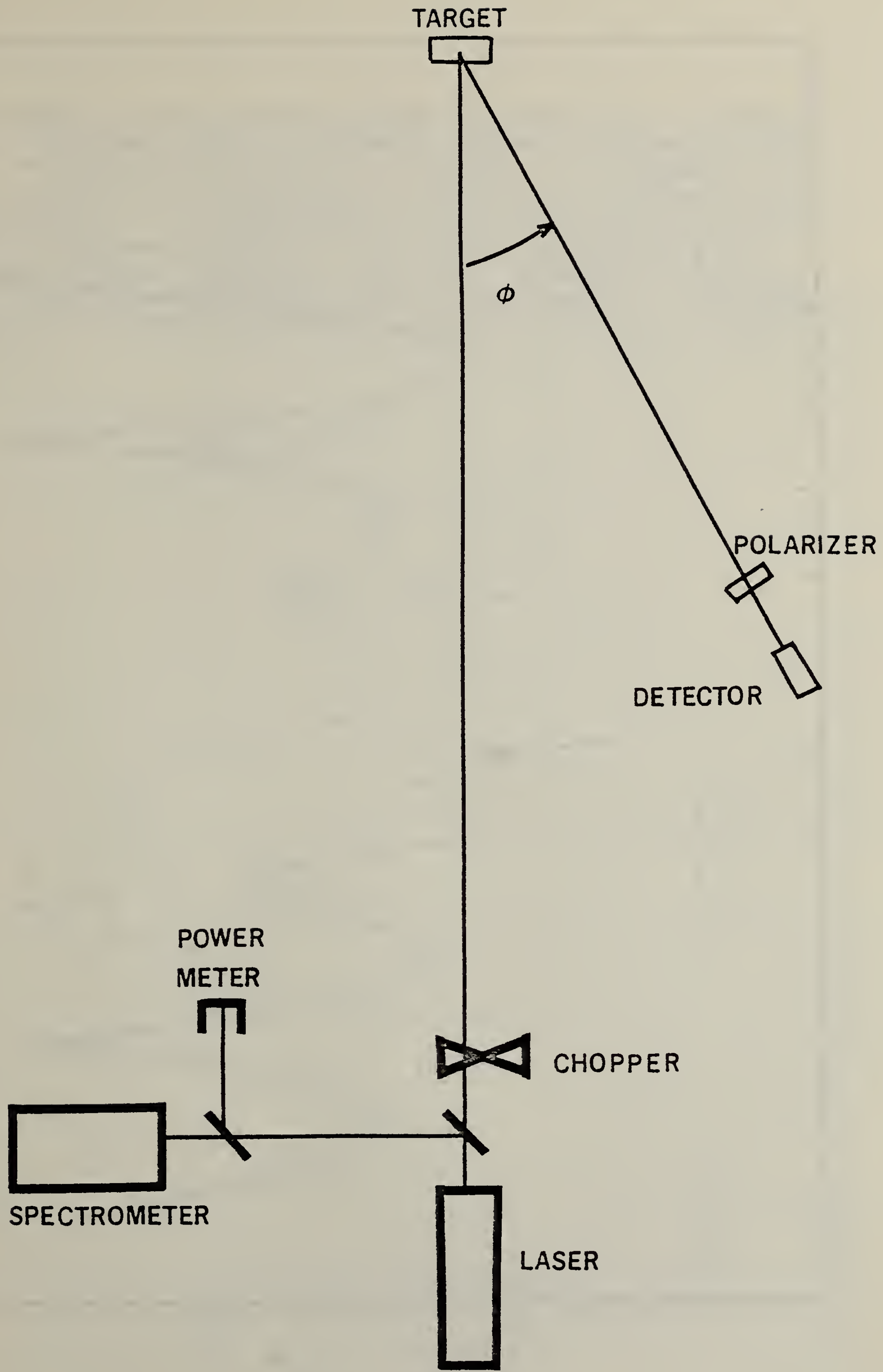

Fig. 12. Schematic of scattering apparatus.

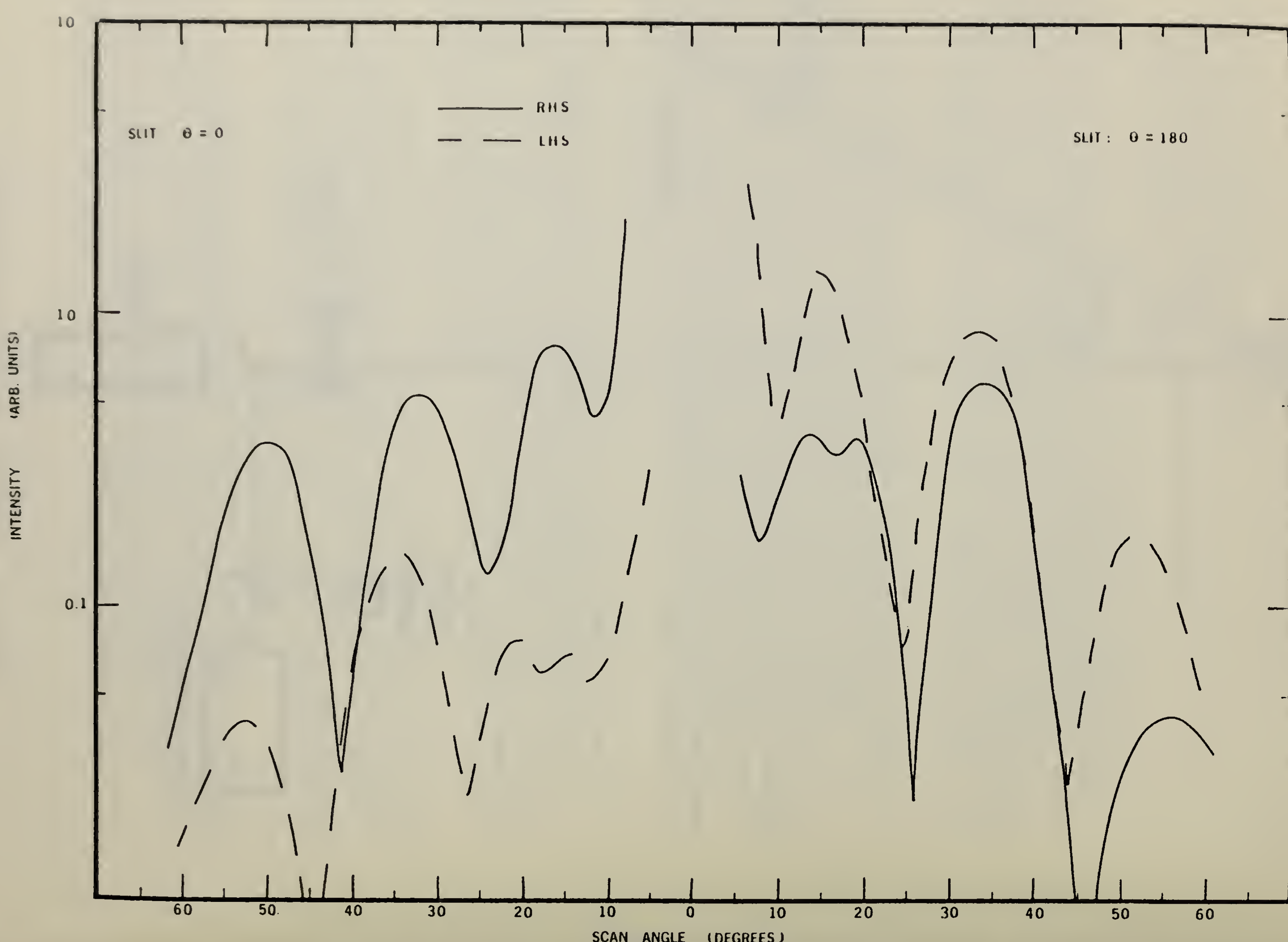

Fig. 13. Typical scattering data showing the double peak shifting from the left-hand side (LHS)

Improvements of the scattering system are being made. A greater emphasis is now being placed on alignment. A special alignment system has been constructed so that the axis of rotation of the detector can be made to coincide with the groove to within 50μm. A further improvement we are making is the replacement of a manual rotation mechanism, which made measurements extremely time consuming and tedious, with a stepper motor rotation mechanism. This latter improvement should make possible future automation of the system by microcomputer. Furthermore, we plan to monitor the output wavelength of the CO_2 laser and the output intensity.

N. Optical Measurement of Surface Roughness

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Mechanical Processes Division
Center for Mechanical Engineering and
Process Technology

We are making progress toward the establishment of a basis for the development of recommended methods for optical measurement of surface roughness. We have completed an extensive literature search and analysis of the resulting papers on optical methods for measuring surface roughness. The analysis has included a distillation of these methods for the ones most suitable for NDE. We are presently in the early draft stage of writing a review paper on NDE and on-line surface roughness measurement which will be published in the fall of 1979 in a new international journal entitled "Precision Engineering." An excerpt from the rough draft of the introduction to this paper follows.

"In this review, we consider alternative techniques to the stylus primarily in terms of their potential for NDE and on-line surface measurement as they may be applied in the metal working industry. We distinguish here between on-line measurements by which we mean real-time, high speed, automated measurements that can be performed routinely and without disruption between stages of manufacturing, and in-process measurements which we define as measurements that can be made while the part is being machined or formed. In-process measurement offers the potential for adaptive control to optimize the finished parts automatically, but it must deal with the environmental problems of part vibration, debris, and surface coolants and lubricants that are generally present during the forming process.

"There is currently great interest throughout industry in the development of on-line surface measurement techniques because of the potential economic benefits in manufacturing. On-line surface inspection facilities would bypass the high labor costs of the stylus technique and would allow for rapid, 100-percent quality control of finished parts. There are, in fact, working on-line surface inspection systems. One example is used at the Ford assembly plant in Puerto Rico, where a laser-based system is used to inspect the surface roughness of the shafts of power steering pumps.

"In this review, we will concentrate on optical techniques for surface topography measurement. Non-optical techniques, which include capacitive and inductive techniques, thermal comparators, and pneumatic gauges, also show some promise and are discussed elsewhere. We will discuss each technique in terms of the criteria of speed, ease in producing an electrical signal, resolution and range, its suitability for studying isotropic and non-isotropic surfaces, its sensitivity to part vibration, its capability for quantitative measurement of surface parameters, and limitation of the types of part geometry which can be studied."

Also, a prototype ultra-high precision mechanical stage has been designed and machining of the stage parts is nearing completion in the NBS machine shop. Assembly, testing and interfacing of the X-Y drive components and stylus transducer to the Image Metrology Facility (described in Section V) should be complete by the end of FY1979. This X-Y stage development is an essential element to achieve the objective because stylus instruments have been and remain the most quantitative technique for measuring surface roughness. Thus, in order to establish a firm basis for the optical measurement of surface roughness, light scattering from surfaces must be compared with area measurements and characterization of surface topography. This stage in conjunction with the Image Metrology Facility will enable the first such comparison to be done for typical industrial surfaces.

The initial design of this stage will employ monolithic flexure pivots as used in the "Piezo-Flex"* stage within a novel "dynamic flexure" configuration that will ensure straight line motion. By using the monolith construction technique, a host of other problems associated with conventional long range stages can be eliminated. A few of the problem areas are:

1) stick-slip friction (horizontal vibrations);

2) bearing noise (vertical roughness of travel);

3) ultra-high vacuum (oil and high vapor pressure lubricants are required).

To adequately meet the requirements of these measurements, the objective of the stage development is to produce a device with the following performance:

Travel	1 cm X 1 cm
Trajectory of Motion	Less than 1 μm over full range
Roughness of Trajectory	Less than 10 nm p-p
Resolution of Driving Mechanism	0.1 μm
Resolution of Position	Resolution of feed-back loop

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* F. E. Scire and E. C. Teague, "Piezodriven 50-μm Range Stage With Subnanometer Resolution," Rev. Sci. Instrum., 49 (12), Dec. 1978.

D. Liquid Penetrant Flow Characteristics

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Center for Mechanical Engineering and Process Technology

Liquid penetrants are frequently employed to locate microscopic, surface accessible defects in solid, non-porous materials. Initial work concentrated on identifying and quantifying the factors which affect the rate and extent of penetration.*

For small defect width to depth ratios, in which defect widths range from roughly 0.01 to 10μm, it was determined that gravitational and non-continuum affects may be ignored. In addition, the axial velocity u was found to be governed by the Poisson equation

$$\Delta^2 u + G/\mu = 0$$

where G is the applied pressure gradient and μ the viscosity. Penetration time then, was shown to follow the Rideal-Washburn relation

$$t \sim \ell^2 \mu / \alpha R \cos\theta$$

where t is time, ℓ defect depth, α surface tension, R defect width and θ the static contact angle. The proportionality constant, however, was found to depend strongly on defect geometry and penetrant application procedure.

The work summarized above ignored the existence of a moving line of contact between liquid penetrant and air. This moving contact line has been the subject of a good deal of theoretical work over the past decade.** One consequence of the moving contact line is that attempts to use the traditional no-slip boundary condition there inevitably lead to an infinite force on the boundary. Currently a slip boundary condition is used as a way around this problem. However, it is not clear that the use of the slip condition is on firm physical ground. In addition, its use leads to a singular pertubation problem, the solution of which is practical for only a few simple configurations.

Work will concentrate then, on examining the boundary conditions at the moving contact line. In parallel, computer codes capable of handling the problem in more complex geometries will be developed.

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* S. Deutsch, "A Preliminary Study of the Fluid Mechanics of Liquid Penetrant Testing," Journal of Research, Vol. 84, No. 4, July-August 1979.

** E.B. Dussan V., "On The Spreading of Liquids on Solid Surfaces: Static and Dynamic Contact Lines," Annual Review of Fluid Mechanics, Vol. 11, 371-400, 1979.

P. A New Image Quality Indicator

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Center for Radiation Research

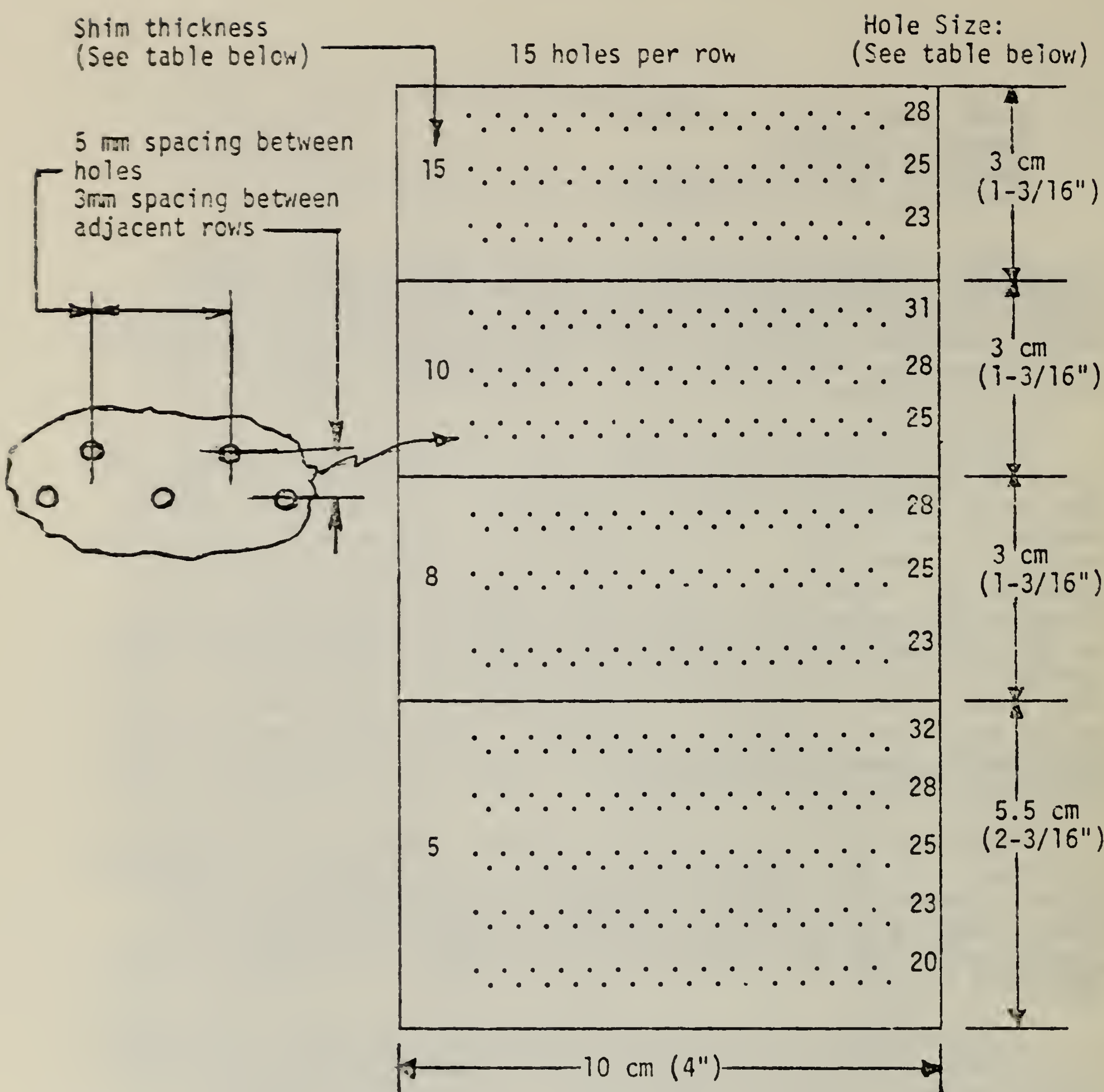
Staff of the NBS X-Ray Physics Group played key roles in the development, by ASTM Committee E-7, of a new image quality indicator (IQI) for assessing industrial radiographic film capability. This device, sometimes referred to as the "Splettstosser plaque," is a multi-hole plaque-type penetrameter which offers promise for quantitative evaluations of other parts of the x-ray image-forming system as well.

This IQI consists of an orderly array of holes in thin plates. The plate thickness varies from .015 in. (0.38 mm) to .005 in. (0.13 mm). The design of this IQI is shown in Figure 14. It is normally used by placing it on a 3/4-in. (1.9-cm) thick steel plate whose maximum surface roughness is prescribed. For the conditions stipulated here, the IQI plus the test plate form a system whose equivalent penetrameter sensitivity (EPS) can be calculated. The actual EPS values vary from 0.94% up to 1.92% and it would be simple to extend this range if needed. A series of round-robin tests was performed which indicate that it is not only feasible to measure EPS using this device but that limiting values of EPS are directly related to film type. It may, therefore, provide a quantitative index of film capability provided all other parameters and conditions are maintained constant.

Many other uses for the device have been suggested. As an EPS indicator it is now undergoing evaluation in our laboratory by comparing it with commercially available devices designed for measuring unsharpness. Tests on such devices for assessing radiographic definition (unsharpness) have been completed and the results are expected to be available shortly.

The advantages of this type of image quality indicator lie not only in its potential for measuring radiographic parameters but also in its simple concept and ease of construction. It can be fabricated in a machine shop with a modicum of equipment by any careful investigator. It is also possible that it will be commercially available provided it is accepted by the industrial community.

IMAGE QUALITY INDICATOR



Step Identification	Step Size
15	.38 mm (.015")
10	.25 mm (.010")
8	.20 mm (.008")
5	.13 mm (.005")

Hole Identification	Hole Size
32	.81 mm (.032")
31	.79 mm (.031")
28	.71 mm (.028")
25	.64 mm (.025")
23	.58 mm (.023")
20	.50 mm (.020")

Fig. 14. Design of IQI.

Q. Real-Time Radiographic System Performance Measurements

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Center for Material Science

Currently the characteristics of a real-time radiographic system are described by individual laboratories for their own convenience. The resolution claimed to be attained by one laboratory using a single isolated small object does not necessarily provide the desired resolution for other laboratories which, for example, deal with a collection of such small objects distributed in materials. In addition to resolution, there are two other important factors for characterizing radiographic systems; speed of obtaining diagnostic results and contrast (or detectability) of objects. The present work describes a method for evaluating the above parameters in a real-time radiographic system. The feasibility of this method is demonstrated using an actual x-ray source for a radiographic system.

The resolution of real time radiographic systems is often considered to be dominated by the resolution of viewing detectors. This is true, if only one can prepare either a mathematical point source or a truly parallel beam. In real-time radiography, unlike films, detectors cannot be placed in direct contact with or very close to object materials; the divergence of the beam, or exactly speaking the apparent source size, cannot be ignored. The resolution of any radiographic (or x-ray optical) system is intimately related not only to optical slit and detector systems but also to the characteristics of x-ray sources. It is, therefore, best to evaluate the quality of radiographic systems including the radiation source as they are in use. The method proposed is based on the following theoretical consideration. The source emits radiation non-uniformly; the radiation from a point of the source has a different angular distribution (divergence) from radiation emitted from different points. This non-uniform property, including different degrees of divergence, is represented by $I_S(x)$, where x indicates a point in the source. A detector which usually has a finite opening sits at the position y.

The objective in evaluating the quality of optical systems is to determine such an expanded quantity $I_S(x)$ for the overall system as accurately as possible. For real radiographic systems, this quantity $I_S(x)$ obviously includes the effects due to the slit systems before, and viewing detectors (image intensifiers, films or counters) after, the object.

Among many possible ways, we choose the two simplest modes of the evaluation of $I_S(x)$. As shown in Figure 15, we use here as an object a plate which consists of two regions of different thicknesses. In mode I, this heaviside object is set at a stationary position and the intensity profile is obtained as a function of position. In mode II, the object is moving at a constant speed, while the intensity is recorded at a fixed position in space as a function of time. For both modes, the intensity is given by

$$I(y;z) = \int dx[\alpha(x)+\beta(x)\, H\, (z - \frac{a}{b} x - \frac{b-a}{b} y)], \qquad (1)$$

where

$$\alpha(x) = I_S(x) \exp [-\mu L], \qquad (2)$$

$$\beta(x) = I_S(x) [\exp \{-\mu(L+\Delta L)\} - \exp \{-\mu L\}] \qquad (3)$$

and

$$H(x) = \begin{matrix} 0 \text{ if } x < 0 \\ 1 \text{ if } x > 0 \end{matrix} \; . \qquad (4)$$

Here the distances a and b between an object and a detector and between the object and a source, respectively, are assumed to be large compared with the thickness of the object L and L + ΔL. The observed intensity distributions are schematically shown in Figure 15. It should be noted here that the characteristics of the radiographic system $I_S(x)$ are truly contained in $\alpha(x)$ and $\beta(x)$.

If we differentiate I(y,z) with respect to the variable y or z, we obtain

$$\frac{\partial I(y;z)}{\partial y} = (\frac{a-b}{b}) \int dx\ \beta(x)\ \delta(z - \frac{a}{b} x - \frac{b-a}{b} y) \qquad (5)$$

for mode I with a fixed z and

$$\frac{\partial I(y;z)}{\partial z} = \int dx\ \beta(x)\ \delta(z - \frac{a}{b} x - \frac{b-a}{b} y) \qquad (6)$$

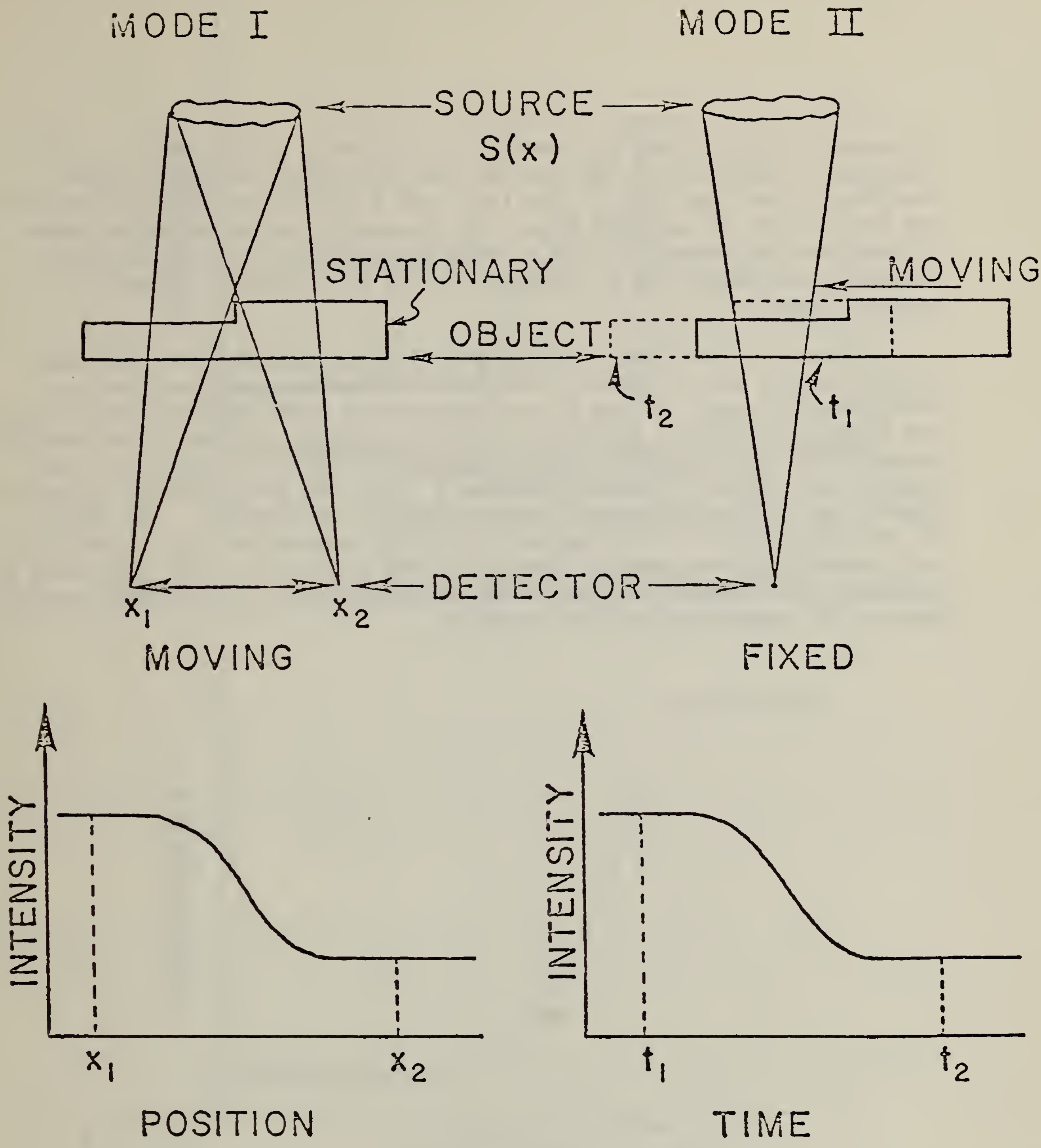

Fig. 15. Possible methods for evaluating the optical performance properties of radiographic systems, such as resolution, detectability and speed.

for mode II with a fixed y. Here $\delta(x)$ is Dirac's delta function. The right hand sides of Eqs. (5) and (6) are both simply related to the function δ, and thus $I_s(x)$. The left hand sides of Eqs. (5) and (6) are the derivatives of measured data. It is usually easier to employ mode II, because the detector is in a fixed position and the intensity is recorded continuously as a function of time as the object moves at a constant speed.

Figure 16 shows the intensity distribution expected from an ideal uniform source and an actual intensity distribution observed from our radiographic system. Using a mini-computer on site, we can differentiate the observed intensity to obtain $I_s(x)$ and further to obtain the Fourier transform of $I_s(x)$, which is the modulation transfer function (or more exactly the optical transfer function.) Also, as seen from Eq. 3, one can obtain the minimum detectable image from this measurement. The details of the application of this method including reproducibility, reliability and convenience have been documented in the past year. This technique also provides simultaneous information on the detectability of objects and the measure of speed required for diagnosis.

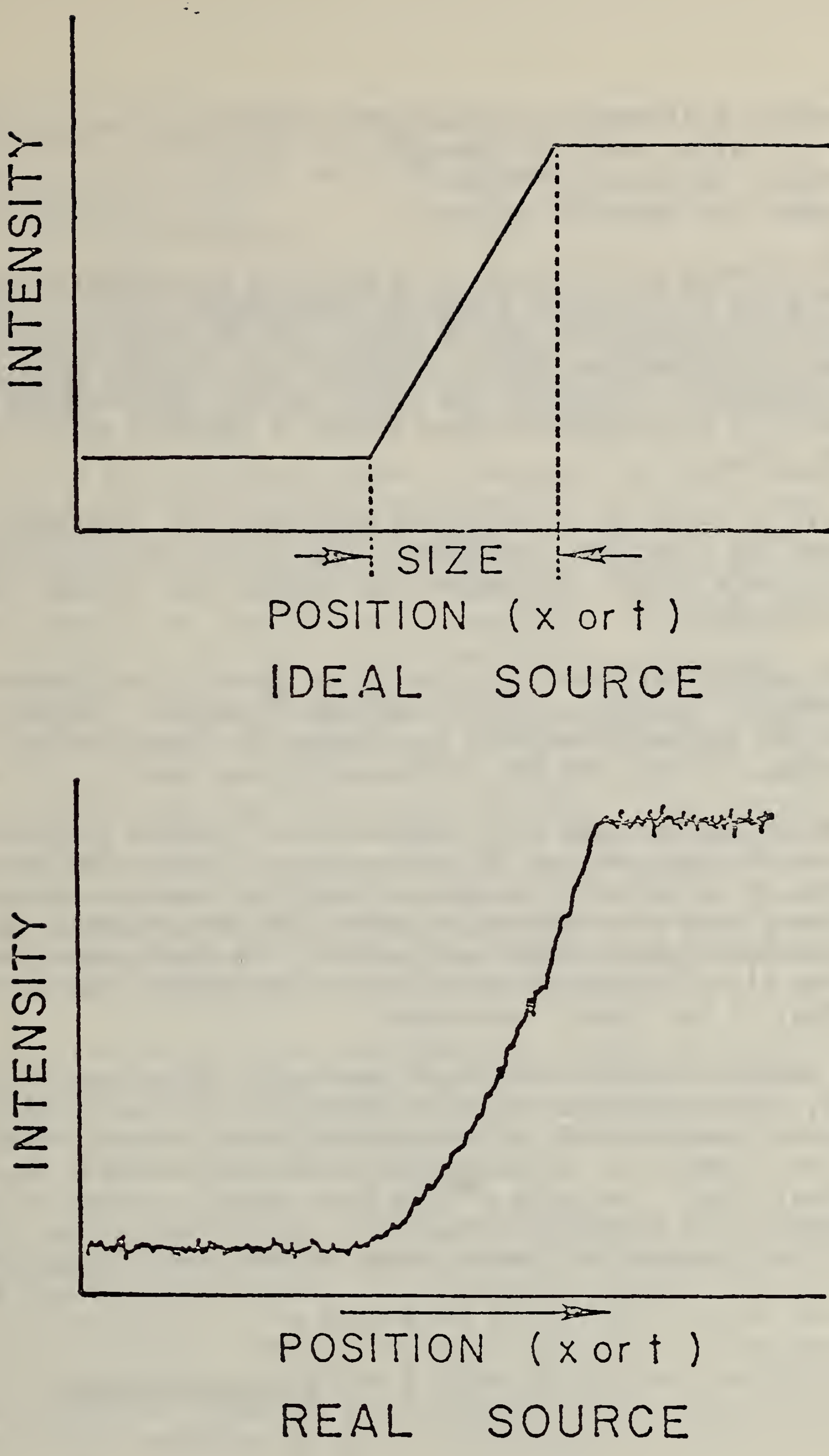

Fig. 16. The ideal intensity distribution from an ideal system and an intensity distribution from a real system, using the proposed Heaviside technique.

R. Neutron Radiography; Standard Measurements of the L/D Ratio

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The purpose of this work is to evaluate two standard methods of measuring the L/D ratio of a neutron radiographic facility, where L is the distance between the neutron source and the image plane and D is the diameter of the neutron source, assuming that the source possesses a finite diameter. In general, an ideal nuclear reactor-based system consists of a distributed neutron source, a defining aperture, and an imaging system.

Next to the flux, probably the most important parameter to be specified for a neutron radiographic facility is the L/D ratio, since it, to a large extent, determines the quality of a neutron radiograph that can be made.

The determination of L/D should involve only the independent measurement of L and D, two well-defined distances. However, beam nonuniformity and scattered neutrons may combine to give an effective L/D ratio which differs from the simple geometrical ratio.

The method employed is a combination of methods proposed to ASTM by groups at Aerotest and the IRT Corporation. It involves the measurements of widths of radiographic shadows of identical neutron-opaque objects which are placed at different distances from the cassette housing the converter and film,as shown in Figure 17. As the object is moved from the image plane toward the source, the width of the shadow increases while that of the "umbra" decreases.

A series of eight radiographs were made, using cadmium wires as the objects, for apertures of 1 in. (2.54 cm) and 2.5 in. (6.35 cm). By mathematical analysis of the radiographic data, it was found that the effective diameter of the aperture, D, was approximately 80 percent of the actual size. The cause of this phenomenon is presently under investigation, but possible explanations are variations across the beam, reflections from the collimator sides and the circular geometry.

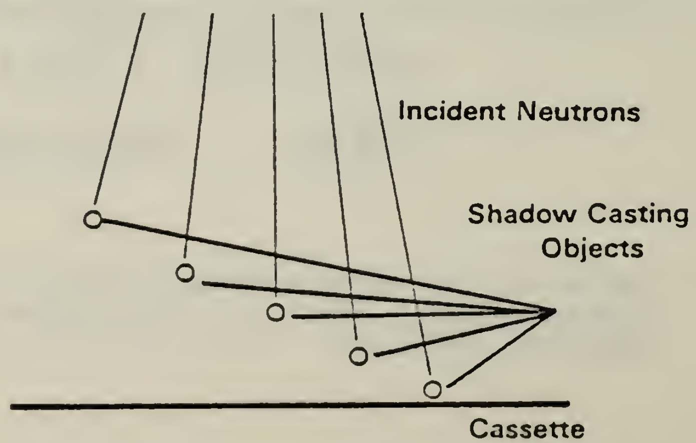

Fig. 17. Cadmium wire test object.

S. Resonance Neutron Radiography for NDE

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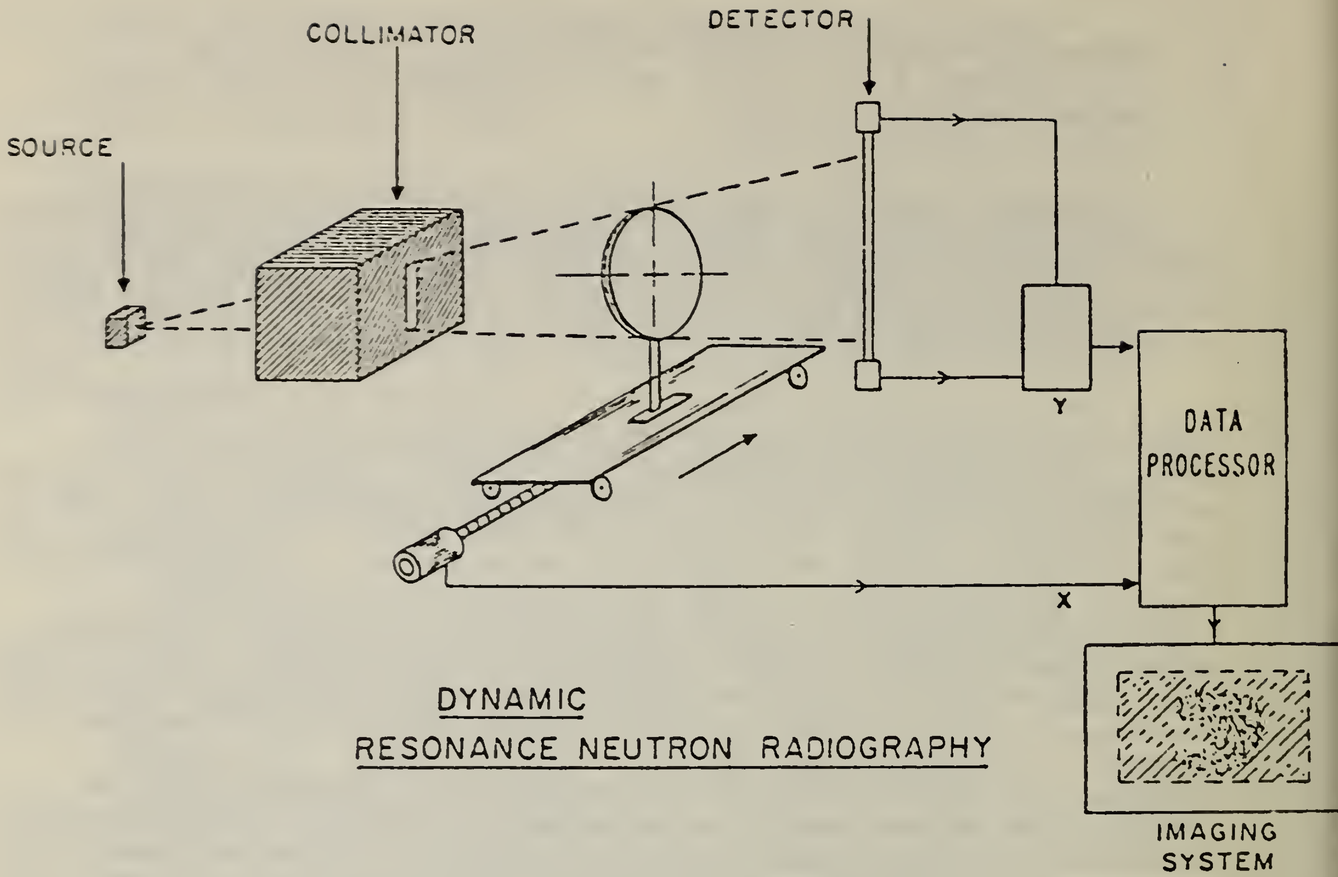
A technique called resonance neutron radiography is being developed. To demonstrate and test the method a broad energy spectrum of neutrons and a linear position-sensitive proportional counter were used with time-of-flight techniques to determine the distribution of silver between two silver-soldered metal disks and to measure the thickness of the solder.

A test facility for resonance neutron radiography has been established; experiments completed confirm the scientific validity of the method. The apparatus is illustrated in Figure 18. The NBS linear accelerator was used to produce a pulsed-neutron beam spread over a wide band of neutron energy. This beam was collimated by a narrow vertical slit and passed through the object to be radiographed. The transmitted intensity was detected in a linear position-sensitive proportional counter which contained 4-atm ^{3}He and 6-atm argon. Position sensing was accomplished by charge division from the resistive electrode. The object under study was moved horizontally by a precision-driven tray. The data on position of the tray (x-direction) and position of neutron detection (y-direction) were fed into a data processor. This system processed the data to form pictures for particular neutron energies of interest. The neutron energy was determined by measuring the time-of-flight of the neutron between source and detector. The method takes advantage of the unique resonance structure characteristic of a given isotope of a given element and, therefore, can determine the position distribution with both elemental and isotopic selectivity.

Testing of the method involved radiographing a brass disk machined to contain a steel disk. The two disks were silver soldered together. Solder was omitted from about a 20-deg portion of the full circle. The objective of the experiment was to determine the distribution of the silver solder and to measure its thickness.

The results of the measurement are shown in Figure 18. The inner darkened circle is the inner hole of the disk and the outer circle represents the boundary of the steel. In looking at Figure 18 it is clear that the distribution of the silver was not uniform and the $\sim$20-deg slot is clearly visible. The thickness of the silver in the more uniform regions averages about 0.025 mm. These results were obtained in a 24-h run using the 5-eV resonance of the isotope ^{109}Ag. The resolution is about 5 mm and the sensitive length of the detector is 20 cm.



DYNAMIC RESONANCE NEUTRON RADIOGRAPHY

Fig. 18. NEUTRON RADIOGRAPH IMAGE OF SILVER DISTRIBUTION

The present experiment centered on determining the presence of silver within an object. Clearly, other elements and isotopes can be similarly identified through their characteristic neutron resonances. The method is useful for elements with resonances below 1 keV and, therefore, permits measurements on elements as light as Mn and Co. The detector spacial resolution can be improved into the submillimeter range for a smaller sensitive length. Improvements to achieve a higher counting rate also are possible.

T. X-Ray Residual Stress Evaluation in the Interior of Materials

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Center for Materials Science

One of the nondestructive methods currently used for measurements of residual stresses in industrial materials involves the application of x-ray analysis for stress measurement. X-ray diffraction phenomena are used to determine macroscopic residual stresses in engineering components. The methodology of analysis and its basic principles are well known. Briefly, when materials are under stress, x-rays are diffracted with a Bragg angle which is slightly different from the Bragg angle expected in unstressed materials. The change in the Bragg angle is related to the alteration of atomic interplanar spacings when the crystal lattice of the materials is strained. As a measurement system, the essential part of this x-ray technique is the accurate measurement of lattice constants (or their changes) in materials by use of well-refined Bragg diffractometry. The surface residual stress can be evaluated from the strains measured by x-ray diffractometry using a set of assumptions regarding material elasticity and homogeneity. Although the accuracy obtained by this technique is, in principle, superior to that of any other method, an obvious shortcoming lies in its incapability of detecting strains (or stresses) in the interiors of bulk materials.

Currently, improved quality control of industrial components demands quantitative information concerning the stress distributions near cracks and residual stress distributions after different types of cold working and heat treating. These demands naturally lead to the necessity of measuring residual strains in the interiors of materials. Ordinary Bragg diffractometry will not be sufficient to respond to these demands. There is an entirely different approach to the x-ray evaluation of residual strains although the approach makes use of the principles of x-ray diffraction. This approach involves the use of energy dispersive solid-state detectors with high-energy x-ray photons. The use of solid state detectors has been introduced very effectively in the fields of scanning electron microscopy (microanalysis) and x-ray fluorescence analysis of materials in the past ten years. It is called energy-dispersive spectroscopy. Unlike these successful applications, this technique has not been applied to the residual stress (strain) measurements of materials. Extremely high resolution and accuracy are required for strain measurements in comparison with other applications. If one can improve the resolution sufficiently and overcome other important technical problems, this new system would be ideal for residual stress measurement in industry; the equipment will display visually and almost instantaneously, and analysis of the data will be made on site by a computer. Also, this system, in general, works better for high-energy photons. High-energy photons also make practical the use of the transmission geometry, since the x-ray absorption coefficient of materials is approximately inversely proportional to the third power of the energy of x-rays.

The use of an energy dispersive system for possible residual stress evaluation was tested in 1973 by Leonard[1] who concluded, however, that this system did not have sufficient accuracy for this purpose. We have proven that his conclusion was premature and it is still too soon to dismiss the possible industrial use of this technique for the evaluation of residual stresses. In doing so, we have proposed[2,3] a method for determining a strain tensor in predetermined volumes in the interior of a material, as shown in Figure 19. In energy dispersive spectroscopy, one is concerned with the energy spectral profiles and peak positions at different energy values, instead of Bragg angles which play a key role in Bragg diffractometry. Lattice constant will be measured in energy dispersive spectroscopy by the energies of diffracted photons:

$$d(A) = \left(\frac{6.199}{\sin\theta}\right) \frac{1}{E(kev)} , \qquad (1)$$

where d is an atomic interplanar spacing related to lattice constants, E is the energy of diffracted photons measured from peak positions of the spectra, and the coefficient including half the scattering angle θ is constant for a given scattering geometry. For our purpose, the scattering angle should be smaller than 30° to ensure complete transmission geometry.

One may claim then that the energy resolution of current solid state detectors is not small enough to reduce the resolution for the evaluation of residual strains. It has been known fortunately that each diffraction profile in the energy spectrum obtained from a solid state detector is very close to Gaussian. If the mathematical shape is known for a spectral profile, then the claim mentioned above can be circumvented: mathematically filling the observed peaks with Gaussian functions, one can determine the centroids (or peaks) of the profiles far more accurately than the $\Delta E/E$ value stated above would indicate. As shown in Figure 20, one can improve by a factor of 100 the accuracy of determining the centroid positions.

Figure 20 shows an example of the observed spectral profile which has been fitted by a Gaussian curve with a linear background. The accuracy of determining the centroid (or peak) position has been found to depend simply upon the counting statistics. Reproducibility of those positions has also been tested; as long as the same predetermined volume is viewed, the centroid position remains identical within the statistical error. As a reference to possible instrumental instability, the Ag $K\alpha$ line spectrum in each run has been fitted with a Gaussian curve. (White radiation was obtained using a Ag target tube.) The Ag $K\alpha$ line result

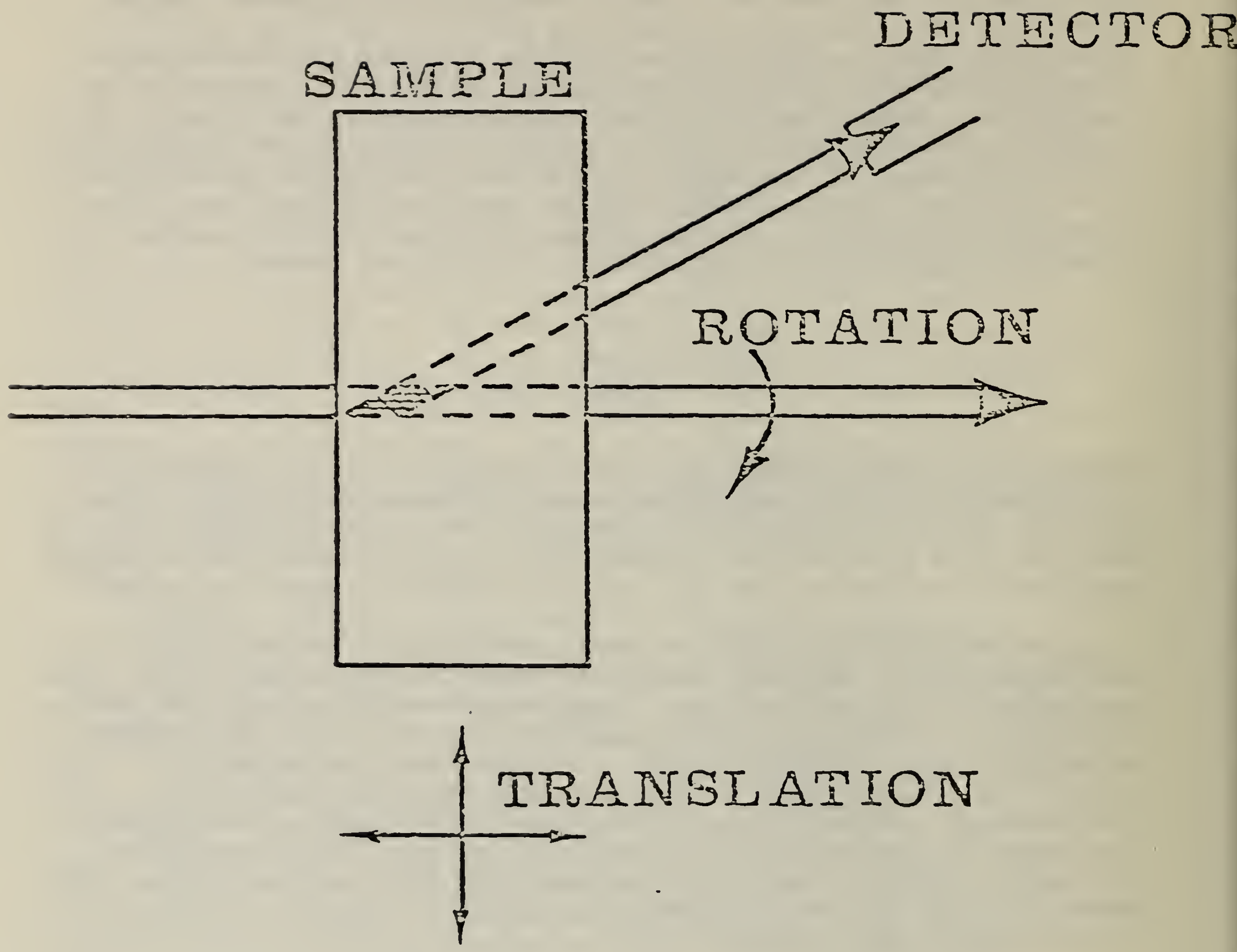

Fig. 19. An example of the geometrical arrangements for the evaluatic of residual strains in a predetermined volume inside materiá The sample is rotated three times around an x-ray beam to g: six independent sets of measurements with two detectors. Tl mapping of strains throughout the volume of the sample is achieved by translations.

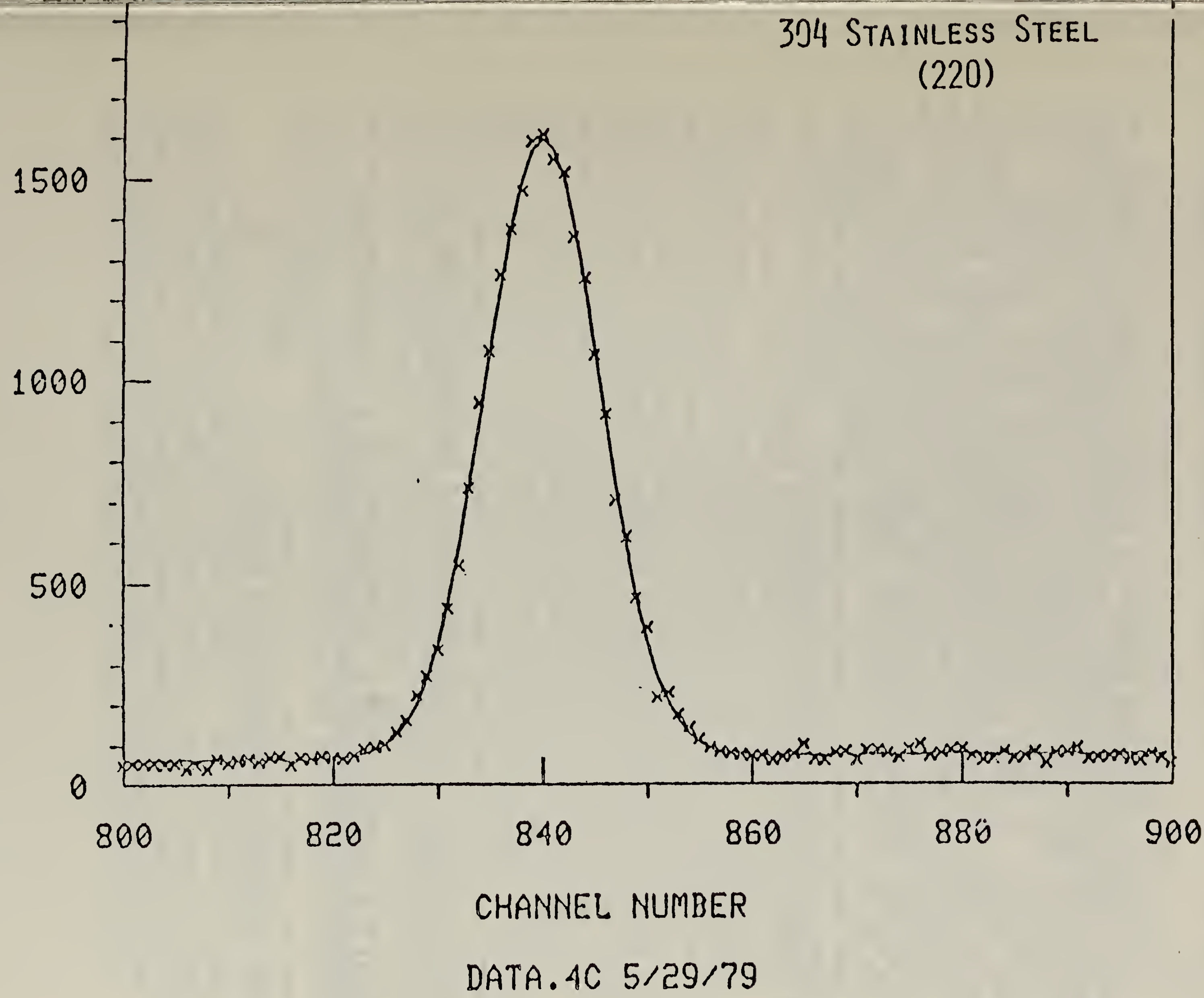

Fig. 20. An example of the observed diffraction profile fitted with a Gaussian curve with linear background.

indicated that the instability, if any, is not sufficient to jeopardize the accuracy in the determination of diffraction peak positions. Our result demonstrates that strains of 5×10^{-5} can be detected with reliable reproducibility, if sufficient counting statistics are established, and strains of 3×10^{-4} can be detected even with moderate counting statistics.

In conclusion, an energy dispersive diffraction system has demonstrated its capability as a useful tool for the determination of residual stresses inside materials when the curve-fitting technique is used simultaneously. The present demonstration has been carried out with low-energy photons. The use of high-energy photons certainly makes more practical the use of these energy dispersive systems for residual stress evaluation. More penetration and increased energy resolution of detectors will improve the resultant accuracy and detectability of strains. Since the energy dispersive system can be made simple and compact, without any delicate moving parts, the system is quite ideal for industrial use on site, particularly when data are handled by a mini-computer. By no means has the energy dispersive system such as used here reached the ultimate resolution; further improvements on x-ray optics and detectors should be made, particularly with high-energy photons.

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[1] Leonard, L., Franklin Institute Research Lab (Philadelphia) Report F-C3454 July (1973).

[2] Kuriyama, M., Boettinger, W. J. and Burdette, H. E., ASNT National Fall Conference, October, Denver, CO, p. 49 (1978).

[3] Kuriyama, M., Boettinger, W. J. and Burdette, H. E., Symposium on Accuracy in Powder Diffraction, June (1979).

U. Wear Condition Monitoring

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This project is concerned with the nondestructive monitoring of the operating capability (health) of mechanical systems in which wear is a significant life-limiting process. This monitoring can take several forms in the field. The most common methods involve measurement of system operating parameters, e.g. temperature, speed, pressure or vacuum, etc. Frequently, these parameters are insensitive to the onset of failure problems and do not offer adequate early warning. More recently efforts have been directed toward vibration monitoring of rotating machinery and systems in order to increase sensitivity. This approach, while promising, is hampered by difficulty in properly interpreting changes in the vibration or acoustic spectrum of a system. Further research is needed in understanding the complicated signal spectrum obtained in such an approach.

In the last several years, considerable effort has been placed in developing wear debris recovery and analysis methods for system condition monitoring. The Navy Department has led these developments although such programs now extend throughout the DoD. These methods generally extract the wear debris from oil lubrication systems and provide a nearly continuous measure of wear metal formation rate. The debris method is frequently combined with spectrochemical methods of oil analysis in the diagnosis of system condition, although the two methods are sensitive to wear products in a different way. Debris can also be recovered from non-oil-lubricated systems, e.g. gas turbine engine ducts. Some of these techniques are being applied in the private sector, e.g. several major airlines and truck fleet systems. Relatively little understanding of the trends in wear characteristics and in debris generation mechanisms exists so far. This lack of a firm basis hampers the further development of debris monitoring methods no matter how promising. Standards of method application and wear debris analysis are needed to properly apply the techniques on a broad scale. This project is oriented to assist in these problem areas through method development, the provision of fundamental understanding, and assistance in standardization activities.

Research efforts have continued in the study of wear debris formation mechanisms in steel and copper metals. The emphasis has been on rubbing (adhesive) wear and on abrasive wear. Abrasive wear is a major cause of failure in lubricated systems, generally the result of particulate contamination from outside the system (seal problems) or from recirculation of wear debris particles (filter problems). We have examined the type of wear debris removed from steel surfaces under various abrasive conditions. Particle size and shape distributions have been obtained. In the case of wear of copper (whose alloys form the usual commercial bearing materials), wear debris studies have been combined with surface and subsurface microstructure studies. Findings include the tendency for abrasive particles to fragment and become imbedded in the ductile metal surface. The identification of cutting chip particles in debris collections does not appear to be a satisfactory indicator of system wear mode. In fact, many debris particles are produced by plastic deformation processes during abrasive wear and must be distinguished from normal rubbing wear particles.

Standardization activities involve the ASTM Committee G-2. A wear debris analysis activity has been started by project staff involving about ten laboratories. Work will be carried out toward possible reference methods of recovery and analysis. A Navy Department meeting is scheduled at which worldwide standardization of ferrographic methods will be discussed. Possible NBS input concerns the area of reference debris particles. The fall meeting of the Mechanical Failures Prevention Group involved a session on on condition monitoring of lubricated systems organized by project personnel.

A Ferrograph system is now available at NBS, purchased through Recycled Oil Program funds. Once established, that capability will be applied to engine condition monitoring in several planned projects. Plans for next year also include the application of acoustic monitoring methods to bench wear systems where debris recovery and analysis will be carried out. In this way, two different methods can be simultaneously applied and compared to indicate system condition. The acoustic monitoring work will be carried out in collaboration with other NDE projects concerned with acoustic methods.

V. Image Metrology Facility

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Center for Mechanical Engineering and Process Technology

With funding support from ONDE and other NBS sources, the NBS Image Metrology Facility, a system of computer hardware and software has been developed, principally from commercially available modules, to enable Bureau staff to obtain dimensional and other analytical information from a variety of image data. The facility can now be used to acquire and store images from photographic transparencies via a scanning microdensitometer and will in the future be capable of obtaining images from a vidicon camera, a scanning electron microscope and surface microtopography instruments.

Images may be stored for analysis and processing in either the three refresh memories of the display processor, two disc drives or a nine track magnetic tape unit. The display processor allows a user to analyze and process the data in three 512 by 512 eight-bit images. Additional features of the processor are a unit which calculates the histogram of all 260,000 data values in 1.15 second, a feedback unit which enables iterative operations to be performed on image data at video rates, i.e., one frame in 1/30 second, and three sets of look-up tables which may be loaded from the host computer which allows the user to perform a wide variety of radiometric transformations and point-by-point algebra on image data.

A large software package of FORTRAN callable subroutines is available from which users may build specialized programs. The package consists of a set of 40 subroutines which perform "primitive" operations with the display processor and a set of utility subroutines. Typical operations which may be performed with these subroutines are:

- Calculate and plot the histogram of an image.
- Draw a graph of the intensity variation along the line joining two cursor locations specified by the user.
- Calculate the distance between two cursor locations specified by the user based on a user defined metric.
- Perform a histogram radiometric transformation on an image.

- Magnify an image by two, four and eight times and select magnified area from original with continuous trackball positioning from user.

- Shift one image vertically and horizontally to bring it into registration with a second image.

- Pseudocolor an image according to a user specified correspondence between gray level and color.

Development of this facility continues. A number of application studies are now in progress.

W. Safety Factors and Mathematical Modeling

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Mathematical Analysis Division
Center for Applied Mathematics

The objective of this project is to propose a mathematical framework (model) to integrate all available quantitative and judgmental information about an engineering system such that the uncertainties associated with the information are transformed into "rational" safety factors for engineering and regulatory decision-making. The framework should be flexible enough to allow experienced engineers and NDE scientists to fine-tune their judgment as more information becomes available.

During the first year of this project (FY 78) a statistical concept of a "rational" safety factor, which incorporates "engineering judgment," was proposed in an invited paper which susbsequently appeared in Nuclear Engineering and Design (Vol. 51, pp.45-54, 1978).

During FY 79 the statistical concept of a "rational" safety factor was applied to the uncertainty estimate of weld defect dimensions from field radiographs. A correspondence was developed between two estimates, one based on field radiographic readings, and the other on carefully conducted laboratory "calibration" experiments. In the case of the 1976 Trans-Alaska Pipeline Girth Weld Data on Defect Depth, an ad-hoc factor of 2.5 which had been proposed, was correlated with a variability analysis of three sets of readings of the field radiographs. The essence of this accomplishment was reported at an international conference (Post-SMiRT-5) held in August 1979 at Berlin.

The Bureau's initiative in calling attention to the need to standardize certain aspects of NDE and inservice data reporting practice resulted in an invitation to present a paper at an international seminar on structural reliability (Berlin, August 1979). The paper, "Inservice Data Reporting Standards for Engineering Reliability and Risk Analysis," will appear in a future volume of Nuclear Engineering and Design.

X. Electric Power Research Institute/National Bureau of Standards Acoustic Emission Program

D. G. Eitzen
Mechanical Processes Division
Center for Mechanical Engineering and Process Technology

Acoustic emission (AE) is a new nondestructive evaluation technique for monitoring structural integrity. It is a passive ultrasonic technique for detecting and locating active structural defects. When a defect in a structure is stimulated, for example by loading in a preservice test or by the actual operating conditions, the defect may emit high frequency stress waves. The detected signals from the stress waves are processed in an attempt to locate and evaluate the significance of a flaw. Applications of AE include its use in determining the structural integrity of aerospace and petrochemical structures, bridges and power plant components, detection of leaks and loose parts and the monitoring and control of on-line welding. AE techniques have also proved a valuable tool in materials research studies. Significant problems, however, remain in the application of AE. One problem is in the reliability of detection of defects. There is a significant potential for false calls since noise sources other than structural defects often exist. Methods for source discrimination and identification are needed to minimize this problem. Another problem is one of extracting the necessary information from the signals in order to determine the character and severity of the source. A third problem area is in interpretation, intercomparison, and repeatability of AE test results. Methods of determining system or subsystem (e.g. transducer) characteristics have not been adequately developed and agreed upon. Methods of calibration and standardization of AE systems and tests are needed.

The need for the development of basic calibration capabilities, theories for AE and experimental verification was jointly recognized by the Electric Power Research Institute and the National Bureau of Standards. A jointly supported project was developed to answer some of the basic questions regarding the use of AE techniques. The objectives of this program are:

> To develop and demonstrate the theoretical basis, measurement techniques and calibration procedures required to evaluate the technical feasibility of using acoustic emission signal analysis for characterizing moving cracks or defects. To provide an acoustic emission transducer calibration capability referred to national standards, and evaluated signal analysis methods for retrieving acoustic emission source signals, and for demonstrations of the feasibility of the methods for predicting defect velocity in structural materials through controlled experiments.

The project elements, progress and plans are briefly described below. Extended discussions of several elements of these tasks follow this review.

Task 1 - Develop calibration capability for AE transducers

The calibration capability for the ultrasonic sensors used for AE measurements is to be referred to national standards and offered as a service. The capability is also to be used to characterize the transducers for the experimental phases of the project.

A theoretical base for the calibration is provided by the exact dynamic elasticity solution to the halfspace with a point force step function. A new dynamic absolute displacement transducer makes implementation of a calibration service possible. Some results of this calibration effort are described in Section Y. Also, recent experiments seem to show the feasibility of developing new piezoelectric transducers significantly better than those presently available.

Task 2 - Develop theoretical basis for moving defects

The objective of this work is to provide a theoretical framework for predicting acoustic emission from specific defects, for the analysis of received signals to determine source information and for discriminating between spurious signals and those from defects. An extended discussion of the results follows in Section Z.

Much of these frameworks, such as the basic transform approach and the Green's function for the infinite plate, have been previously developed and reported within this program. More recent efforts have focused on more specific singal processing problems associated with source deconvolution and calibration problems. Many concepts and algorithms for filtering and deconvolution have been pursued. Decimation techniques and an adaptive integration method have been pursued for deconvolution. A faster, more accurate numerical method for calculating the wave propagation in an infinite plate is being investigated. A new Fourier transform-type algorithm with less distortion than other algorithms has been developed. Some of the processing work is aimed at deconvolution in the presence of noise. Some specific theoretical source and propagation problems still need to be solved.

Task 3 - Correlation of theory and experiment using transparent materials

The objective is to correlate experimental AE results from growing defects in transparent materials with the theoretical analysis of moving defects. These controlled experiments will demonstrate the feasibility of the AE analysis methods for predicting defect characteristics.

Three experimental configurations for producing cracks in glass have been fully developed: ball impact, indentor and local thermal tension. Independent verification shows the glass crack event occurs in less than a microsecond so that measurement of velocity by AE is not feasible in this material. On the other hand a characterization of the event in terms of a force time history at the source through deconvolution of the measured displacement (absolute AE signal) has been demonstrated in collaboration with Task 4. The AE events in glass were shown to agree well with the existing theory. Further comparison awaits additional specific theoretical solutions.

Task 4 - AE measurements in structural steels

The objective is to perform exploratory tests for measuring crack characteristics in structural steels, particularly those important for nuclear reator pressure vessels in the electric power industry. The experiments should help determine the feasibility of AE analysis for determining defect characteristics in structural steels.

The signal acquisition and digital data processing systems were further developed. Deconvolution methods for two sensor-source geometries were implemented (see Section AA for details and some results). A large sample of A535B steel was obtained. Data are being taken on this and similar steels using several configurations, including a bolt-loaded stress corrosion specimen and cracking of an embrittled plate with an indentor. Further work on deconvolution of simulated and defect events in plain and welded steel specimens is planned.

Y. Acoustic Emission Transducer Calibration/EPRI

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A calibration capability is being developed for acoustic emission (AE) transducers and is ready to be offered as a measurement service. This activity is partially supported by the larger EPRI/NBS Acoustic Emission Program described in the preceeding section and by ONR. The objective is to determine the sensitivity versus frequency of AE transducers over the approximate range of 100 KHz to 1 MHz. This is accomplished by obtaining time histories from the transducer under test and from the NBS standard transducer, both mounted on a large (4800-lb) steel transfer block. The input is a simulated source on the same surface of the block as the transducers. The resulting time histories are digitized and processed in frequency space to obtain the desired measure of spectral response.

Additional physical aspects of the calibration have been recently explored by means of several experiments:

1. Repeating the same configuration of source and test transducer to determine precision.

2. Varying the test transducer's angle of orientation to determine the effect on transducer response; the dependence of the response on orientation is small but observable indicating the presence of horizontal sensitivity in commercial transducers.

3. Varying the location of receiver in an arc around the source; this yielded no significant dependence of test transducer on arc position.

4. Varying the source-to-receiver separation showed no significant deviation from the expected 1/r relationship.

Calculated aspects of the calibration were also checked by means of computer experiments. We found that time deconvolution methods and the FFT method gave equivalent transducer responses. Deconvolution of a wave form from the standard transducer by the calculated surface pulse waveform yields a total system impulse response as an indicator of combined errors in the system. These waveforms showed the errors to be minor. The spectrum of the surface pulse was obtained. As a check, the original waveform was reconstructed from this spectrum. An inverse with respect to convolution was obtained for the surface pulse.

The data collecting system has been upgraded to increase the sampling rate by a factor of four.

It was observed that transducers having a circular area of contact, when excited by wave motion travelling in the surface, exhibit a circular aperture type of interference which introduces zeros in their frequency response. If these zeros occur in the range of interest, the transducer is not likely to be useful as a calibration transfer standard. This suggests work is needed on the development of more appropriate transfer standards. Initial feasibility experiments already conducted indicate that transducers which could better serve as transfer standards (and, perhaps, as event sensors) could be developed.

The calibration method described has a number of caveats. Some of these could be resolved by also developing an epicenter measurement of transducer response, which is our plan.

Z. Acoustic EmissionTheory/EPRI
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This activity is part of the joint EPRI/NBS program on acoustic emission. Work in the theory of acoustic emission has been divided into four parts:

1. Deriving the transfer function formalism

2. Dealing with the plate geometry

3. Signal processing and deconvolution

4. Modelling AE from defect sources.

1) The transfer function formalism which may be summarized by the equation:

$$V(\omega) = T_{k\ell}(\omega)\underline{\dot{\sigma}}_{k\ell}^{A}(\omega)$$

allows one to express the voltage frequency response from a given AE signal received at a given transducer in terms of a transfer function containing the material geometry and tranducer characteristics and a mean stress drop tensor, $\underline{\dot{\sigma}}^{A}$, associated to the emission event. The transfer function representation is not generally valid, but requires both restrictions and assumptions. However, it appears likely that this formalism may well be valid in many technological important applications.

If one wished to invert the AE information to find the source stress drop tensor, the transfer function formalism leads to certain important implications: 1) Unlike scalar transfer function problems where inversion information can be obtained directly from power spectra, to find $\underline{\dot{\sigma}}^{A}$ from $V(\omega)$, multiple transducers yielding complex spectra with phase information are generally necessary. Generally, six separate observations are needed to separate the six stress components. 2) Bandpass filtering to eliminate the defect size effect may also be required, which together with other filtering to eliminate noise, can, at best, yield band limited information about the source.

2) Stress wave propagation in an isotropic plate has been solved in this program based on a new Fourier transform technique developed in collaboration with Prof. John Willis of Bath Univeristy, England. This technique allows one to compute the transient response in an elastic plate due to various stress sources located up to about ten plate thicknesses from the detector. Examples of the response to various point

sources applied as step functions in time at five plate thicknesses from the detector are shown in Figures 22 and 23; the geometry is indicated in Figure 21. Some of these curves, such as G_{31}, also directly yield dipole response functions. Other dipole responses are obtained by numerical differentiation. Note that G_{31} tends to have opposite values when the source is changed from the top to the bottom surface. This fact, which is much more pronounced when the source is somewhat nearer the detector, may allow the determination of source depth for such defects as mode I cracks oriented perpendicularly to plate faces. Other theoretical consequences of the plate solution are being studied. These results are accurate to better than 6 digits. The apparent jumpiness of the curves is due to multiple reflected wave arrivals.

3) In order to invert the signals received from the transducer to obtain information about the AE source, it is necessary to carry out a numerical deconvolution procedure. A formally similar deconvolution procedure is required to produce a transducer calibration. Because of the high priority associated to this latter need, work was temporarily suspended on the plate solution results to look at deconvolution algorithms. Most of the ordinary algorithms in use today were found to be non-robust, frequently yielding incorrect answers to deconvolution with the type of signal needed for tranducer calibration. The problem occurs because of numerical noise amplification produced by deconvolution algorithms. New algorithms were developed. Two of these require more extensive computer facilities. One of these methods is being explored for signature analysis potential. The third, developed in cooperation with Dr. Diane O'Leary at the University of Maryland, is still being studied. Since there are a great number of fields where deconvolution is used, the importance of these new algortihms extends well beyond acoustic emission.

4) The theory for acoustic emission from expanding planar dislocation loops has been developed. An example of the AE signals from a circular loop expanding with constant velocity for a fixed period of time in an infinite body is shown in Figure 24.

The need to study real defects as opposed to simpler calibration type sources introduces a number of requirements due to the generally lower signal level of real defects and the tensor nature of the defect signal. The high speed data acquisition system and its associated minicomputer system are now being procured. Low noise preamplifiers are being built to mount directly on the back of well-characterized capacitive transducers, each of which will be recorded by a separate high-speed analog-to-digital converter. The current A-to-D converters have only 8-bit resolution with concommitant lack of dynamic range, and we

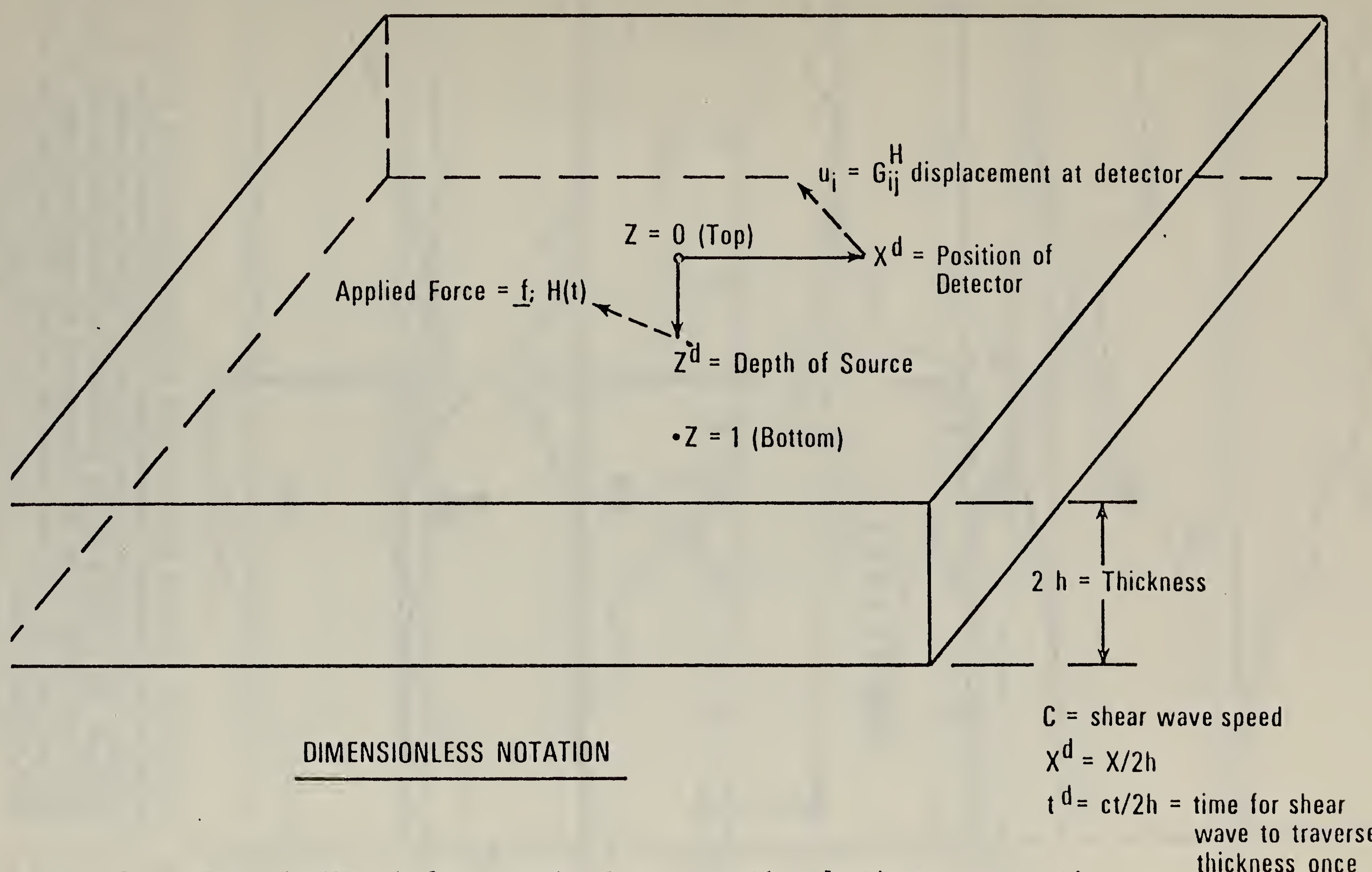

Fig. 21. Geometry is dimensionless notation for representing elastic wave propagation in infinite plates. The x_3 direction is chosen vertical and the x_1 direction is chosen as the horizontal direction connecting the projected image of the source on the top face with the detector, also on the top face.

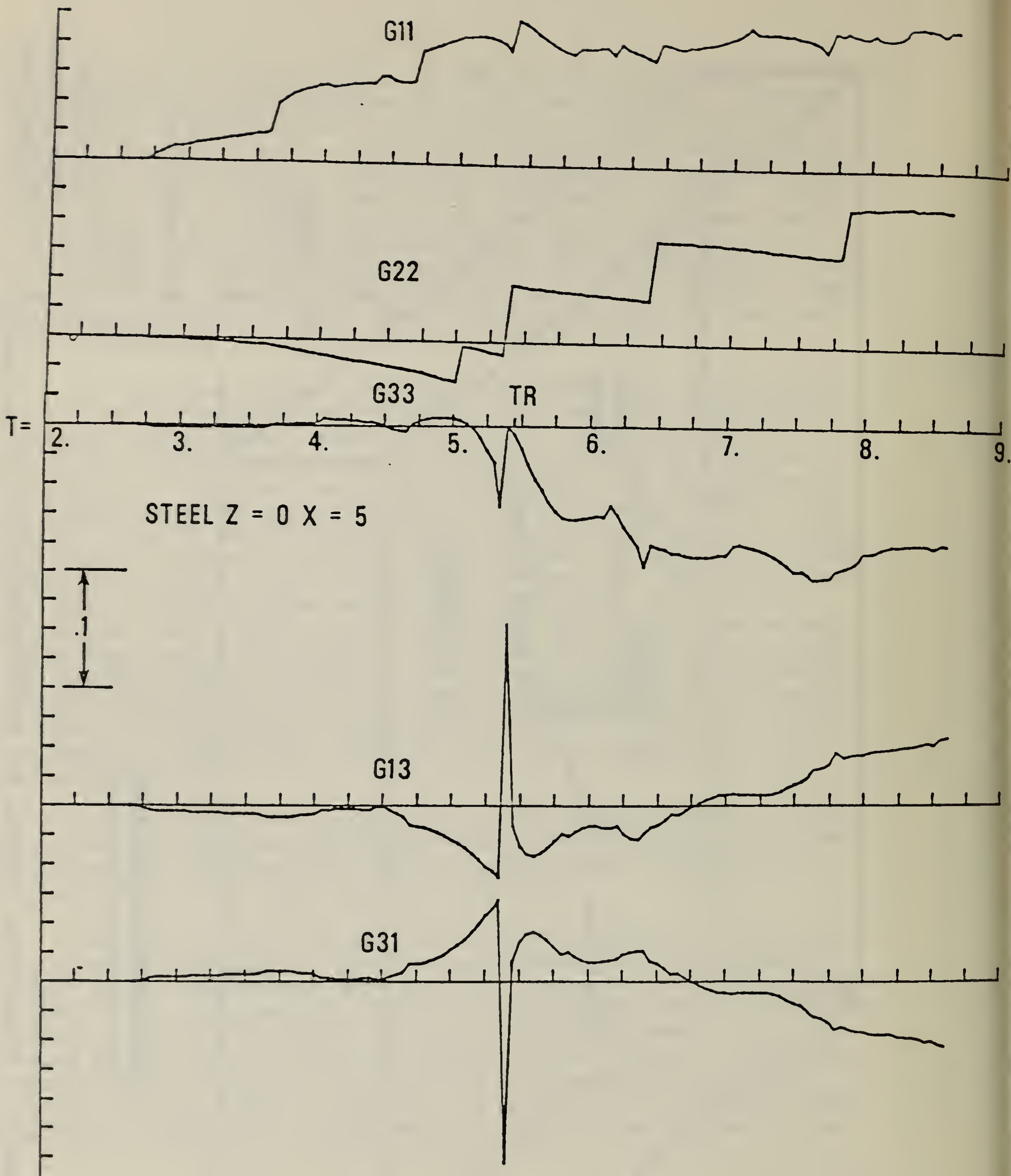

Fig. 22. Response of infinite plate to step function point source with source and detector on the same plate surface. Elastic constants chosen at typical stee values. Time units are dimensionless. As indicated in Fig. 21, the first index on the G refers to the direction of motion of a surface particle while the second index gives the direction of the applied force. All other compone of G are zero in this configuration. Small "TR" on the time axis is the Rayl wave arrival time.

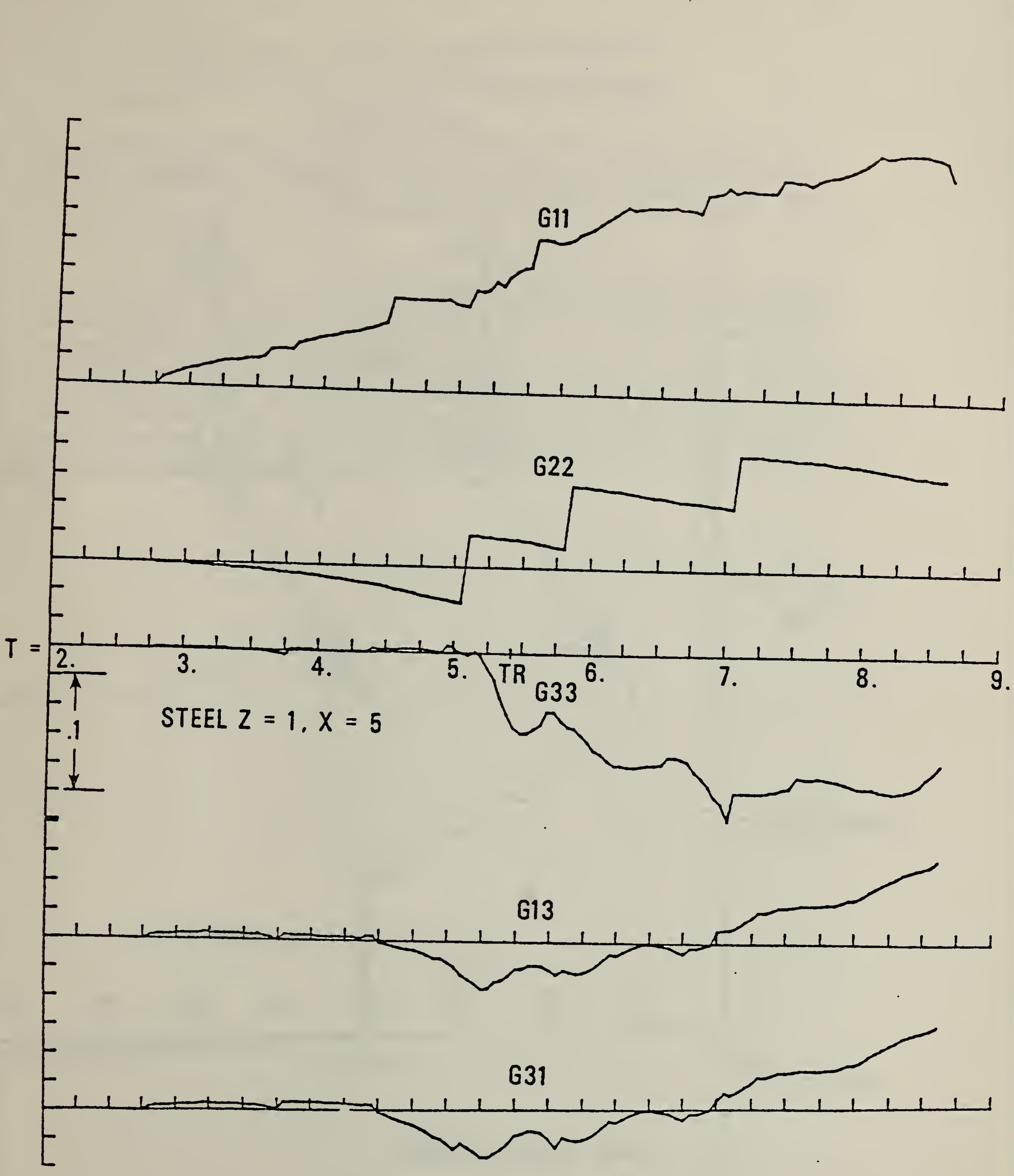

Fig. 23. Response of infinite plate to step function point source with source and detector on opposite plate surfaces. Elastic constants chosen at typical steel values. Time units are dimensionless. As indicated in Fig. 21, the first index on the G refers to the direction of motion of a surface particle while the second index gives the direction of the applied force. All other components of G are zero in this configuration. Small "TR" on the time axis is the Rayleigh wave arrival time.

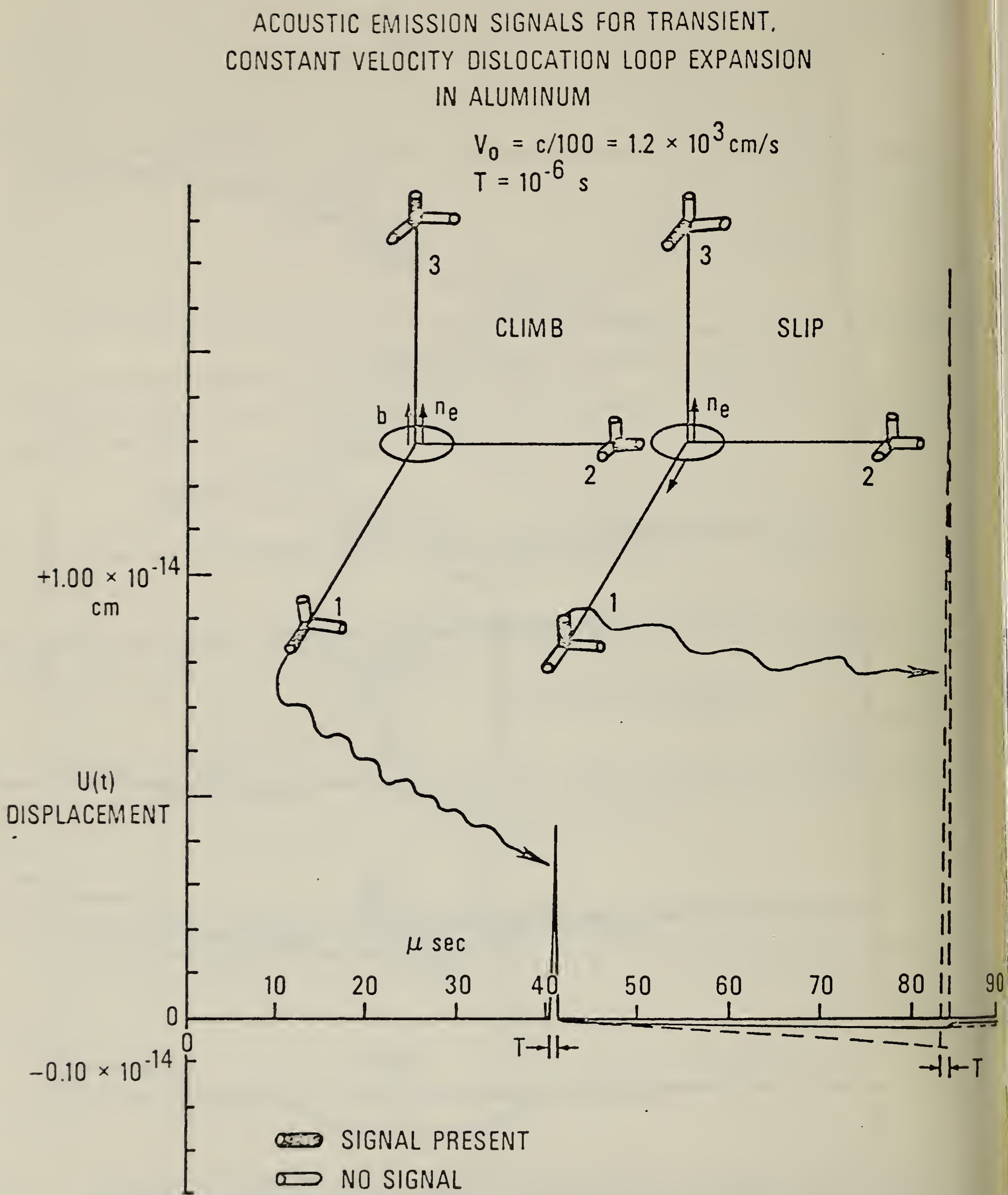

Fig. 24. Acoustic emission from a circular loop expanding for 1μsec with constant velocity. The only two non-zero emissions from slip are the sam The two radial motions from climb also coincide. The normal motion response in the x_3 direction is not shown but resembles the radial motion with a stronger peak at the longitudinal wave arrival time and secondary response of opposite sign to that of radial motion.

are currently studying means for increasing the dynamic range. The outputs from the analog-to-digital converters are dumped at very high speed into a remote high-speed peripheral making it possible to record multiple emissions in a single test in a laboratory environment separated from the computing facility.

We have chosen to study experimental acoustic emission signals in steel plate specimens, and are currently studying indentation loading methods under a variety of conditions to select the most promising experimental configurations. Our goal is to study microcracking under controlled conditions where the cracking mechanism will vary from ductile to brittle. While not yet fully evaluated, brittle type cracks have been produced at the surface in the heat-affected zones of welds (both continuous and spot) and in high carbon steel which was given an embrittling heat treatment.

AA. Acoustic Emission Source Characterization/EPRI

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One of the objectives of our work on acoustic emission (AE) is to determine the source characteristics of the AE event by analyzing the leading part of the detected AE signals. While detected AE signals contain potentially useful information about the deformation source mechanisms of a structure under load, signal processing techniques such as threshold counting, RMS recording, energy measurement, peak detection, and spectral analysis often fail to extract such information unambiguously. The difficulty lies both in the inherent complexity of the deformation mechanism and in the lack of understanding of the source mechanism, the wave propagation details, and the physics of the sensor's mechanical-to-electrical conversion process.

Instead of taking an empirical approach to establish the correlations between the detected AE and the observed possible deformation mechanism, we approach the problem by constructing a simple test system which consists of three main ingredients: a true displacement sensor (capacitive transducer), a simple structure (either a large block or a plate), and known theoretical impulse-response functions for specific sensor-source relative locations. We first establish the validity of these ingredients by testing with simulated AE of known step-function time dependency generated by breaking glass capillaries. Unknown sources are then introduced, one at a time, into the system for determination of their time functions. Consequently, the difficult problems of the evolution of an AE signal can be studied separately as three parts: the calibration of a sensor, the transient wave propagation in a structure and the source mechanism. This approach thus provides a base for the quantitative analysis of all aspects of problems related to AE sensor, structure and source.

In the past year we have further developed a signal processing scheme which essentially resolves the inverse problem--to find the source time function from the detected AE signal. We have constructed explicitly the inverse impulse response functions with respect to convolution for two source/sensor geometries; one of these is shown in Figure 25. For the first time any unknown vertical force time function resulting from impact opening can be determined simply by recording the displacement at the epicenter (or on the same surface) and convolving the recorded displacement with the inverse function. Many simulated AE signatures have been determined and signatures of some AE from brittle fracture have also been obtained. Two examples of the source reconstructed from the measured displacement are shown in Figures 26 and 27. This inversion technique not only demonstrates the possibility of characterizing AE sources completely and absolutely but also has applications in the measurement of force-time functions such as impact, a measurement that is required in many experimental mechanics problems.

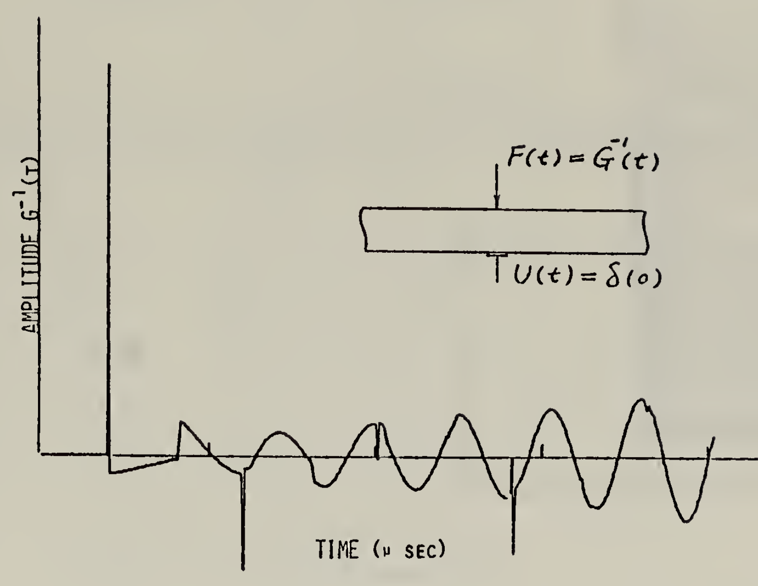

Fig. 25. Inverse function $G^{-1}(t)$ at the epicenter of a large plate. The curve is obtained by direct inversion of the impulse response function. Physically, the curve is the force function required to produce a displacement at epicenter of delta function time dependency.

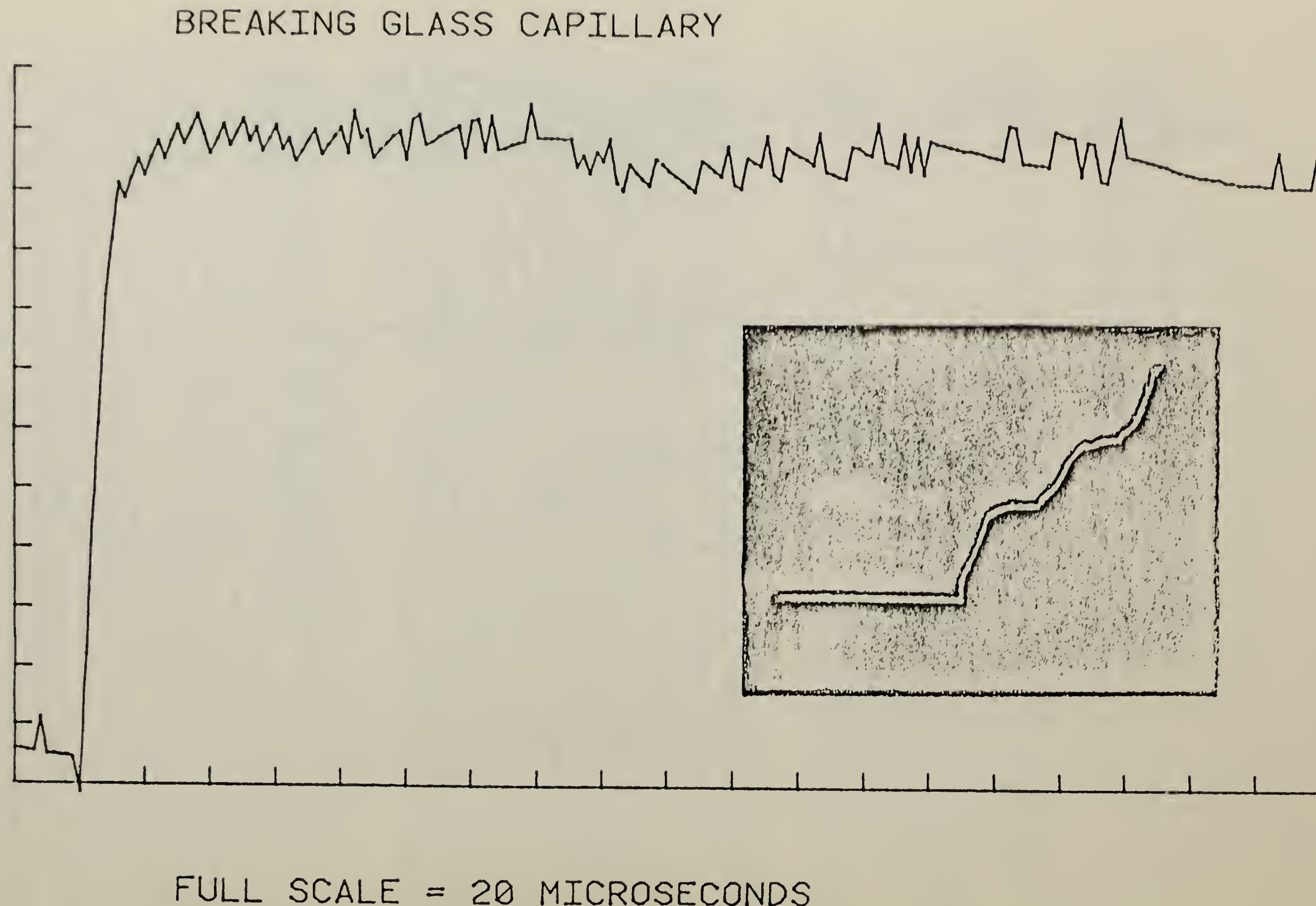

Fig. 26. Source force-time function of breaking glass capillary obtained by time-domain deconvolution of recorded epicenter displacement. Insert trace is the recorded epicenter displacement.

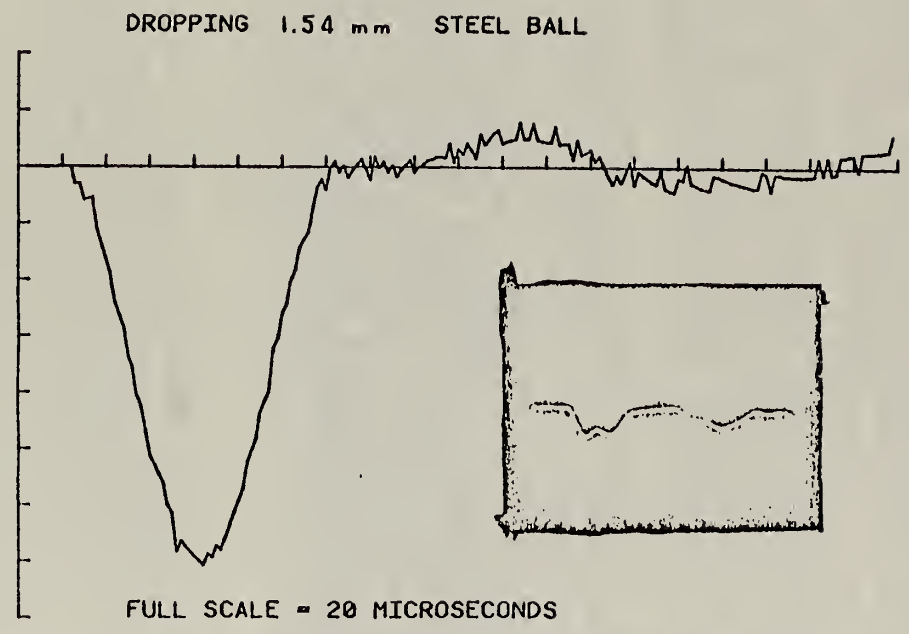

Fig. 27. Source force-time function of dropping ~1.5 mm steel ball from 5 cm height. Insert trace is the recorded epicenter displacement.

BB. Ultrasonic NDE Standards/DARPA

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National Measurement Laboratory

An NBS interagency report to the Defense Advanced Research Projects Agency on "An Appraisal of Current and Future Needs in Ultrasonic NDE Standards" has been completed. This work, supported also by NBS, assesses the current status of NDE ultrasonic standards and calibrations and attempts to determine current and future needs in this area. In addition to many specific recommendations, the following are some of the broader recommendations and conclusions: (1) The most important need in current and future ultrasonic NDE measurement methods is for transducer characterization. (2) New and more quantitative techniques will not in general make obsolete current standards and calibrations; in many cases these will continue to be useful with relatively minor changes. (3) Because of the wide variety and requirements of ultrasonic NDE techniques, it is important to deal with standards needs from the viewpoint of an integrated system rather than as isolated and individual requirements.

In addition to the above report, the following work was completed as part of the same study. (1) A Comparison of American and European Ultrasonic Testing Standards, S. Golan, NBSIR 79-1790, which reviews 27 documentary standards from nine industrialized countries and two international organizations. (2) "Ultrasonic Transducers for Materials Testing and Their Characterization", by W. Sachse and N. Hsu, Physical Acoustics, Vol. 14, Academic Press (1979). A summary of the literature on ultrasonic NDE standards is being prepared for publication as an NBS interagency report. It is expected that those reports as well as the report to DARPA will serve as resource documents for ultrasonic NDE standards.

CC. Reliability of Ultrasonic Weld Inspection/NRC

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The Pressure Vessel Research Council (PVRC) performed a round robin on the ultrasonic inspection of reactor welds. Twelve inspection teams inspected three large weld specimens which simulate the nozzle area of a reactor pressure vessel. The specimens were welded with an attempt made to introduce defects at specific locations. A small study, funded by the Nuclear Regulatory Commission, concerns an evaluation of the procedures and data resulting from the round robin to see if the probability of finding flaws can be determined in a statistically meaningful way. The actual analysis of the data is possible future work.

There are several problems associated with the determination of the reliability of defect detection from the information and data presently available. There are some questions regarding the design of the round robin and the inspection procedures and serious questions about the true condition of the specimens. Any errors in introducing the defects into the weld region as to location or size result in serious coloration of the inspection data; the true locations and sizes of the defects are not known.

The first analysis of the data indicated a very low probability of defect detection. However, there was reason to suspect that deviations between actual and assumed flaw locations account for part of this low probability. A difference between actual and assumed flaw location results in two apparent inspection errors: one miss call and one false call. A second analysis of the data which used the data itself as criteria for flaw location (a two-coincidence method) yielded a somewhat higher probability of defect detection but still not as high as the method seems capable of yielding.

To date the raw data have been obtained from the PVRC and discussions with some participants and experts have been accomplished. The data and methods are being evaluated by NBS experts in ultrasonic NDE and statistics. Alternate data analysis schemes are being considered.

DD. Application of Nondestructive Evaluation to Construction/Army

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Center for Building Technology

The use of NDE methods in construction is being studied for the U.S. Army Construction Engineering Research Laboratory. At present, when the military has a building constructed, it largely depends on the contractor to use materials meeting the design specifications and to adhere to acceptable construction practices. As a check on the performance of the contractor, construction inspectors have been used by the military. However, often these inspectors do not have the necessary skills and experience to be effective. Therefore, the military plans to modify this approach. A modification being considered is the incorporation of quality assurance testing of the building materials prior to acceptance of the completed building. The quality assurance testing will be based upon NDE techniques.

NDE techniques applicable to concrete quality assurance will be identified and assessed. Assessment of the NDE techniques will be based on considerations of usefulness of information obtained, reliability, level of expertise required to use the equipment and to interpret the results, and cost-effectiveness. Then, the use of NDE for the quality assurance of certain other building materials will be assessed.

Important factors which should be part of quality assurance testing of concrete, and NDE methods which can be used to assess them, have been identified. These factors include strength, uniformity, density, surface finish and thickness of concrete, and conditions and location of steel reinforcement. Applicable NDE methods have been divided into two categories. First are those methods which have proven to be reliable and whose results are generally accepted by concrete technologists. In the second are NDE methods that are either being developed or whose reliability needs to be demonstrated.

A report is being prepared which gives the principles, cost, advantages and limitations of applicable NDE methods. In addition, the feasibility of combining NDE methods to obtain an improved assessment is being explored. A field demonstration of selected NDE methods will be carried out by making tests on actual structures. The purpose of this demonstration is to convey, to military personnel responsible for design and construction of military facilities, the usefulness of NDE in quality control and quality assurance programs.

EE. NDE of Moisture in Roofing Systems/Air Force

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Center for Building Technology

Moisture in insulated built-up roofing (BUR) systems causes many premature roof failures. Moisture in the insulation will reduce the useful life of a membrane by causing blistering, splitting, wrinkling, and deterioration of the membrane.

Early detection of moisture in roofing is needed if rapid deterioration is to be prevented. The usual methods of inspection, however, are slow, costly, require cutting samples from the roof, and seldom provide conclusive results. The best hope for improvement of inspection and maintenance procedures is through nondestructive evaluation (NDE) which could possibly provide reliable identification of wet areas of insulation and membrane.

There are currently a number of promising NDE methods, such as nuclear backscatter gages, electrical capacitance instruments, and infrared thermography, being used to measure the amount of moisture in roofing systems. Because the state-of-the-art is such that many uncertainties exist, a comprehensive study was conducted to compare the accuracy, validity, and applicability of these methods so their proper role in roofing inspection, maintenance, and repair programs can be established. The research results obtained in this study were performed in conjunction with a program to determine the effect of moisture and its distribution on the thermal conductivity of insulated roofing systems.

A state-of-the-art report describing the NDE methods currently available, their technical mechanisms of operation, and the currently published NDE laboratory and field data (1979) is near completion in work being done for the Air Force.

Laboratory NDE tests were conducted to assess the performance and response of two nuclear meters, three electrical capacitance instruments, one infrared themography apparatus, and two types of microwave equipment. With the exception of the microwave equipment, the instruments (or service including the instrument) are sold commercially. The two types of microwave equipment are in developmental stages; one type is being developed by the NBS/Boulder Electromagnetics Division and the other at the U.S. Army Cold Regions Research Engineering Laboratory (CRREL).

NDE laboratory measurements were taken on a total of seventy, 60 cm by 60 cm (two feet by two feet) roofing specimens, each consisting of a roofing insulation board with an attached, four ply, BUR membrane. The seventy specimens included five common roofing insulations, each tested in one- and two-inch thicknesses.

Both gravel and smooth surfaces were evaluated; two thicknesses of asphalt were included. NDE responses were taken with the specimens placed on concrete, steel, and wood decks.

Moisture was induced in the two feet by two feet specimens by means of a water vapor pressure difference. This was accomplished by maintaining the insides of two large chambers, measuring 244 cm by 488 cm (eight feet by sixteen feet) in area, at 38°C (100°F) and 100 percent relative humidity while keeping the outside of the chambers at 10°C (50°F) and 25 percent relative humidity. Some of the insulations, such as fiberboard, gained moisture rapidly while the foamed plastics absorbed moisture at a much slower rate.

To determine the distribution of moisture, 275 cores were taken from the wet insulation. The cores were sectioned and oven dried to determine the moisture content and distribution. The coring data will be used to study the effect of the distribution of moisture on the NDE responses.

With the exception of the infrared themography method, NDE measurements were taken at about fifteen moisture content levels for each specimen. For all the combinations (insulation type and thickness, surface, and asphalt thickness) and including replication, about 75,000 NDE readings were taken.

The NDE data have been computerized and are currently being analyzed. An unbiased technique of comparing the ability of each of the NDE methods to detect moisture is being developed.

Based on an extensive analysis of the NDE data the accuracy, validity, and applicability of the NDE methods will be evaluated. Guidelines and recommendations will then be established for the selection of the most effective methods of determining moisture in built-up roofing systems.

APPENDIX

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(5) "An Appraisal of Current and Future Needs in Ultrasonic NDE Standards", G. Birnbaum, D.G. Eitzen, NBSIR 79-1907 (1979).

(6) "X-Ray Magnifier", W.J. Boettinger, H.E. Burdette, M. Kuriyama, Rev. Sci. Instrum. 50, No. 1, pp 26-30 (Jan. 1979).

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(44) "Resonance Neutron Radiography Using A Position-Sensitive Proportional Counter", J.W. Behrens, R.A. Schrack, and C.D. Bowman, Trans. Am. Nucl. Soc. 32, 207 (1979).

(45) "Acoustic Emission of Polymers Under Tensile Load", A. Peterlin, Probing Polymer Structures, Advances in Chemistry Series 174, Jack L. Koenig, Ed., pp. 15-23 (1979).

B. NDE Meetings at NBS

The NDE program has been active in sponsoring NDE meetings, both symposia and workshops. The purposes behind this significant meeting activity include (1) drawing attention of the industrial community to NDE, (2) providing a good record of the state-of-the-art, (3) providing a forum for information exchange, (4) helping our NBS staff meet individuals active in NDE and learning the status of current work in the field, and (5) providing a mechanism for NDE people to discuss their NDE standards needs.

During this past year, NBS sponsored a Symposium on Eddy Current Characterization of Materials and Structures. The meeting, held in cooperation with ASNT, ASTM and IEEE, was held at NBS on September 5 to 7, 1979.

C. NBS Seminars on NDE

A list of NBS-NDE seminars held during the past year is given in Table VII.

Table VII
1978-1979 NBS-NDE Seminars

Speaker	Date	Topic
Paul Packman Southern Methodist Univ.	Oct. 18, 1978	Quantitative Evaluation of High Resolution Fluorescent Dye Penetrants
Tom G. Kincaid Dave W. Oliver Bill L. Chu GE Corporate R&D	Dec. 5, 1978	An Overview of NDE at GE Corporate R&D
Robert B. Pond, Sr. Johns Hopkins University	Mar. 5, 1979	Pitfalls that May be Encountered by the Use of ASTM E-399
Donald O. Thompson Rockwell Int'l Science Center	April 17, 1979	Review of Elements of the ARPA/AFML Quantitative NDE Program
Charles M. Vest University of Michigan	April 20, 1979	Holographic Interferometry and its Application to Nondestructive Evaluation
Gerald V. Blessing Naval Surface Weapons Center	May 17, 1979	Nondestructive Evaluation of Metal Matrix Composite Properties
Lydon J. Swartzendruber National Bureau of Standards	June 15, 1979	Magnetic Leakage and Force Fields for Artificial Defects in Magnetic Particle Test Rings
Gerald L. Anderson American Gas & Chemical Co.	June 21, 1979	Leakage Testing - - Still the Mystic Art
Emanuel Segal Defense Ministry of Israel, and Visiting Assoc. Professor Drexel University	June 28, 1979	Recent Developments in NDT of Adhesive Bond Joints
Leslie W. Ball Consultant	Aug. 15, 1979	NDT as a Factor in Product Liability Prevention
Haydn Wadley NDT Centre, AERE, Harwell	Aug. 16, 1979	Acoustic Emission During the Deformation and Fracture of Metals

D. Awards

There were several recognitions of NBS-NDE people during this past year. Awards include the following:

Industrial Research, IR-100 Award:

NBS was recognized for work on the x-ray magnifier. NBS scientists involved in this development include M. Kuriyama, W. J. Boettinger and H. E. Burdette.

NBS Applied Research Award:

M. Linzer was cited in recognition of his development of a highly sensitive ultrasonic system - a major development imbodying new technology, improving technological and theoretical approaches - immediately applicable to medical diagnosis and nondestructive evaluation of materials.

Department of Commerce Silver Medal:

Two NDE people were presented the DoC Silver Medal in ceremonies at DoC on October 30, 1979.

J. T. Fong is recognized for technological contributions in mathematical analyses for materials science and engineering.

H. Berger is recognized for his outstanding leadership and scientific contributions in the field of nondestructive evaluation and for having attained national prominence in this area.

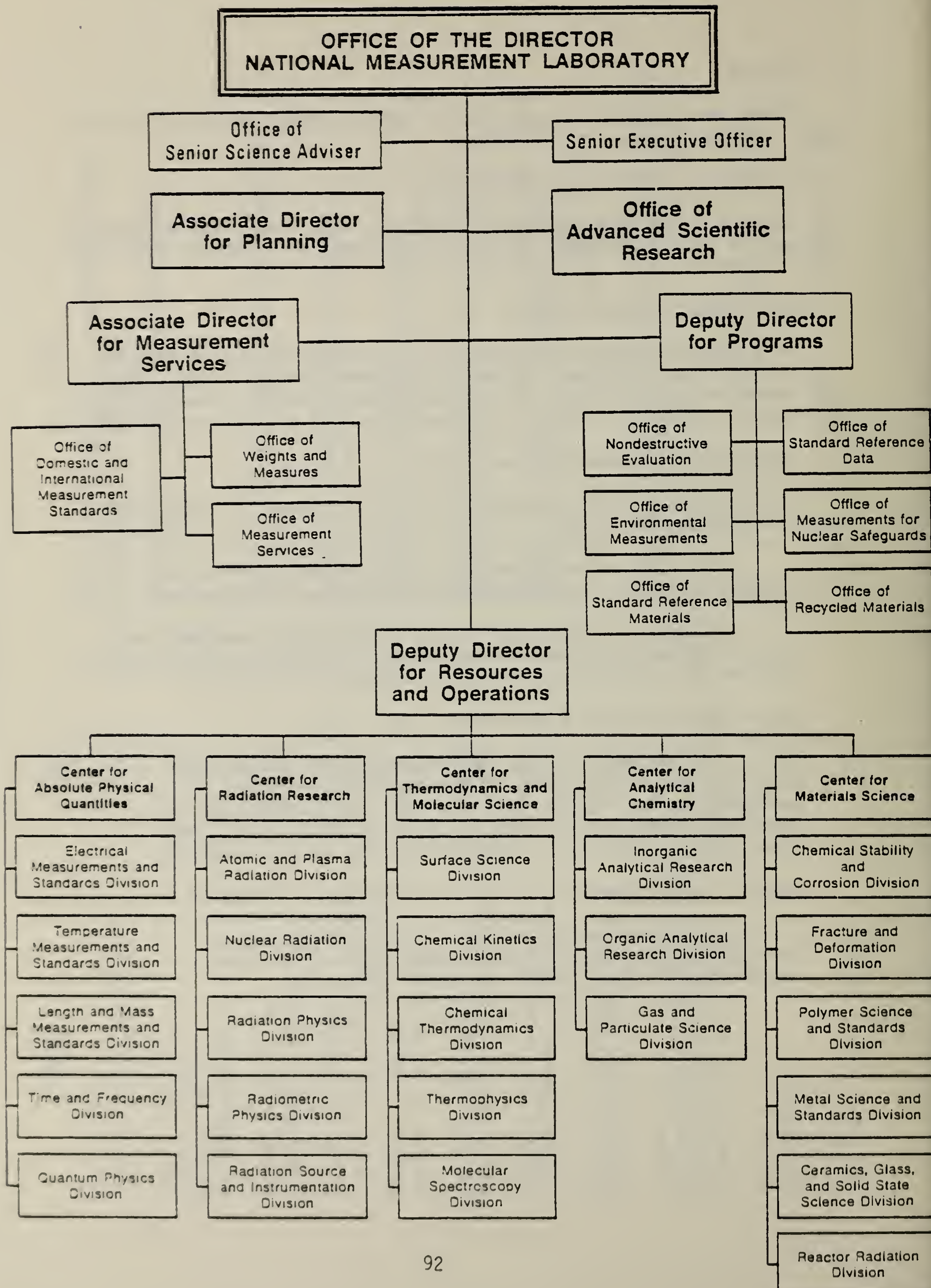
Department of Commerce Gold Medal:

G. G. Harman, Jr., was recognized for his outstanding contributions to the field of interconnection bonding of semiconductor microelectronic devices. His nondestructive bond pull tests and his acoustic emission measurements have been widely adopted and acclaimed by industry and government.

Hugh M. Huffman Award of the U.S. Calorimetry Conference:

E. J. Prosen was cited for his outstanding work in calorimetry and chemical thermodynamics which included microcalorimetry of cardiac pacemaker batteries.

E. NML Organizational Chart



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15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This report is the second in the series of annual reports on the National Bureau of Standards (NBS) program in nondestructive evaluation (NDE). These reports summarize the program's activities and plans. The focus of the present report is on the program's activities in Fiscal Year 1979 and on its plans for the next five years.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Acoustic; annual report; eddy currents; inspection; magnetic particles; nondestructive evaluation; penetrants; radiography; statistics; ultrasonics; visual-optical tests.

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