Federal Laboratory Nondestructive Testing Research and Development Applicable to Industry

**S. A. Smith, PNL Project Manager
N. L. Moore, PNL Program Manager**

February 1987

**Prepared by Energetics, Inc.
for Pacific Northwest Laboratory
under Contract DE-AC06-76RLO 1830
with the U.S. Department of Energy**

**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute**

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor Battelle Memorial Institute, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government of any agency thereof, or Battelle Memorial Institute. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, or Battelle Memorial Institute.

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE MEMORIAL INSTITUTE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

NTIS Price Codes
Microfiche A01

Printed Copy

Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
151-175	A08
176-200	A09
201-225	A010
226-250	A011
251-275	A012
276-300	A013

FEDERAL LABORATORY NONDESTRUCTIVE
TESTING RESEARCH AND DEVELOPMENT
APPLICABLE TO INDUSTRY

S. A. Smith, PNL Project Manager
N. L. Moore, PNL Program Manager

February 1987

Prepared by Energetics, Inc.
for Pacific Northwest Laboratory
under Contract DE-AC06-76RLO 1830
with the U.S. Department of Energy
under Agreement B-K8583-A-V

Pacific Northwest Laboratory
Richland, Washington 99352

ABSTRACT

This document presents the results of a survey of nondestructive testing (NDT) and related sensor technology research and development (R&D) at selected federal laboratories. The study was conducted by Energetics, Inc. for the Pacific Northwest Laboratory (PNL) under contract with the U.S. Department of Energy (DOE). The objective of the study was to identify and characterize NDT activities that could be applied to improving energy efficiency and overall productivity in U.S. manufacturing. Numerous federally supported R&D programs were identified in areas such as acoustic emissions, eddy currents, radiography, computer tomography and ultrasonics. A Preliminary Findings Report was sent to industry representatives, which generated considerable interest. Surveys of federally supported R&D should be continued, with the broadest possible coverage and periodic updates.

SUMMARY

More than 700 federal laboratories in the U.S. conduct basic and applied research and development (R&D) in numerous and diverse fields pertinent to energy, space, defense and other missions. Although the products of their efforts can be of enormous value in improving the energy efficiency, productivity and competitiveness of private industry, they may remain relatively unknown due to the time and resources required to identify and analyze them.

This document presents the results of a survey of nondestructive testing (NDT) and related sensor technology R&D at selected federal laboratories. This study was conducted by Energetics, Inc. for the Pacific Northwest Laboratory (PNL) under contract with the U.S. Department of Energy. The objective of the study is to identify and characterize activities that are potentially applicable to improving energy efficiency and overall productivity in U.S. manufacturing industries (Standard Industrial Classifications 20 through 39).

The principal steps in this effort were to:

- identify the federal laboratories and staff conducting NDT R&D potentially applicable to industry
- contact the most promising laboratories to identify and characterize relevant activities
- prepare formatted descriptions of relevant NDT activities
- review preliminary findings with industry representatives
- prepare a final report.

Thirteen laboratories were surveyed: eight through visits and five through mail and telephone inquiries (Table S.1). Numerous federally sponsored R&D efforts, research capabilities, and facilities were identified in the course of this project. Descriptions of 9D such "activities" are presented in Section 3.0. These federal NDT activities are potentially applicable to a

TABLE S.1. Laboratories Surveyed

Laboratories Visited

1. Air Force Wright Aeronautical Laboratories (AFWAL)
2. Lawrence Livermore National Laboratory (LLNL)
3. Los Alamos National Laboratory (LANL)
4. NASA Langley Research Center (LaRC)
5. NASA Lewis Research Center (LeRC)
6. National Bureau of Standards (NBS)
7. Pacific Northwest Laboratory (PNL)
8. Sandia National Laboratories (SNL)

Laboratories Surveyed by Mail and Telephone

1. Ames Laboratory (Ames)
2. Army Materials Technology Laboratory (MTL)
3. Argonne National Laboratory (ANL)
4. Idaho National Engineering Laboratory (INEL)
5. Oak Ridge National Laboratory (ORNL)

wide range of industrial operations, particularly product quality, process control, safety, and materials characterization. Some examples are described below.

- Acoustic emission (AE) work under way at several laboratories could result in improved in-service inspection and monitoring of pressure vessels, bridges, aircraft, chemical processing systems, metallurgical processes, and machining operations. For example, PNL has developed a prototype AE instrument system for continuously monitoring flaws in reactor pressure vessels, which is currently being used to monitor an inlet weld nozzle at the Tennessee Valley Authority's (TVA) Watts Bar Nuclear Reactor. The work could prove widely applicable to flaw detection in pressure containment systems and perhaps extend use of AE monitoring where previously only radiography and ultrasonics were considered. Several National Bureau of Standards (NBS) efforts could improve upon and expand utilization of AE technology. These include development of an inexpensive AE source

location system, and investigation of AE in various metallurgical processes and in monitoring tool wear and chip formation during machining.

- Important eddy current (EC) work is also ongoing at the federal laboratories surveyed. Development of EC techniques and equipment is a major area of NDT research at ORNL, and theoretical work at ORNL has aided the development of EC systems elsewhere. Eddy current applications at Oak Ridge National Laboratory (ORNL) include examination of seam welds in the sheath of superconductor cables, stainless steel plate welds and steam generator tubing. Researchers at NASA Lewis Research Center (LeRC) have developed an EC turbine engine disc-crack monitor designed to detect cracks while the turbine is in operation; the EC sensor and inspection approach could prove useful to other real-time high-temperature inspections. At the Air Force Wright Aeronautical Laboratories (AFWAL), work is under way to develop and evaluate various novel EC probes and signal processing for EC inspections. Similarly, at PNL, work is being conducted on EC instrumentation and imaging of EC inspections.
- Radiographic work, generally applicable to defect detection in a wide range of materials and to assembly and operational verification, is a major focus of federal laboratory NDT work. Two areas of work at the Lawrence Livermore National Laboratory (LLNL) are worth noting: low-energy radiography and a computerized radiographic materials characterization system. Both can maximize use of radiographic techniques; the software for the materials characterization system should be of interest and can be made available to industry. At Los Alamos National Laboratory (LANL), work on dynamic x-ray imaging (up to 2000 frames per second) is a powerful tool to analyze systems in motion (e.g., compressor operation). Combining optical and x-ray capabilities allows both kinds of images to appear in a synchronized presentation. AFWAL is also active in real-time radiography, and developments at AFWAL related to improved screens should be of interest to industry.

- In the related area of computer tomography (CT), important work is also ongoing. Information on developments and applications of CT at various federal labs should be of interest to many in industry, where the technology is developing rapidly, and might help speed transfer of the technology. Strong capabilities exist at Sandia National Laboratories (SNL), LLNL and LANL. For example, SNL is continuing to develop a fan-shaped 32-detector array for computer tomography work with micro focus and other x-ray generators. Also of note is the work supported by AFWAL related to CT including the Integrated Blade Inspection System being developed by General Electric and work by Aerojet and ARACOR.
- A large portion of NDT work at the federal laboratories surveyed involves ultrasonic techniques. An example is the pulsed phase locked looped (PPLL) ultrasonic instrument, developed at NASA Langley (LARC). The instrument, which characterizes ultrasonic natural velocity, has been demonstrated (or investigated) for use in a number of applications including determination of preload in critical fasteners, work hardening, stress profiles, residual stress in metals and stress in rock samples. The PPLL has been licensed to several companies. An automated multiviewing (multiprobe) ultrasonic transducer and associated data processing software developed at Ames is a useful new tool for flaw detection and characterization. PNL has designed an advanced ultrasonic inspection instrument that was subsequently evaluated by AFWAL; the instrument has performed well and is now available commercially.

Various ultrasonic techniques are being developed or investigated for composites NDT. Several important activities supported by AFWAL include an Automated Real-Time Inspection System (ARIS) that permits hand-scan of an area and a C-scan display of the scanned area; a Mobile Automated Ultrasonic Scan (MAUS) system for large area inspection (i.e., scanning 100 sq ft/hr to detect delamination 2 inches or larger); and exploratory work investigating leaky Lamb

waves for composites inspection, which offers the potential for good sensitivity to many inhomogeneities (e.g., delamination, porosity, etc.) in composites. A phase insensitive transducer developed at LaRC has been used to advantage in several aspects of composites NDT.

Several efforts involving ultrasonic determination of temperature distribution or solidification interfaces in hot metals are applicable to various metal processing operations, particularly the continuous casting of steel. Related efforts at NBS and PNL are aimed at development of an in-process sensor for determining the internal temperature profile of a hot metal form based on measurement of ultrasonic velocity. NBS work on the in situ monitoring of the solidification interface of metals during solidification or melting, which utilizes the acoustic impedance difference between solid and liquid phases, is addressed toward preventing breakouts during continuous casting. Another effort applicable to metals is work at Ames Laboratory on ultrasonic characterization of porosity in cast aluminum, which could lead to improved process and quality control for aluminum castings.

Activities often encompass more than one NDT method, addressing, for example, particular materials or inspection problems. Several efforts are directed toward NDT of ceramic materials (components and joints), primarily involving ultrasonic and radiographic techniques. Work at Argonne National Laboratory (ANL), Idaho National Engineering Laboratory (INEL), LeRC, NBS, ORNL and other laboratories is applicable to ceramics fabrication and flaw detection in ceramics used in heat engines, heat exchangers, fossil energy systems, and other components. This work should be valuable in advancing NDT of ceramic materials and promoting the use of such materials. ANL has a program directed toward nondestructive evaluation (NDE) of stone materials to assess acid rain damage assessment. ANL has also developed, in support of light-water reactor performance, an acoustic leak detection system that has performed better than commercial moisture sensitive tape. PNL conducts a program to nondestructively detect and evaluate stress-corrosion cracking in digester vessels. Also of interest at PNL is the development of imaging systems including imaging for AE, EC, ultrasonic, and microwave inspections.

In addition to specific work efforts, a variety of facilities and equipment exists at Federal laboratories that may be of interest to U.S. manufacturing industries. An example is the Ultrasonic Test Bed at LLNL to facilitate ultrasonic inspections, particularly for complex shapes; the signal processing software, which is the key to the technology, should be adaptable to similar (though likely smaller) systems in industry and can be made available to them. Acoustic microscopes at LLNL and LeRC are applicable to particular NDT problems. When completed, the cold neutron research facility at NBS should open up important opportunities for NDT researchers. For example, small angle neutron scattering has potential uses for material property characterization and process monitoring for polymers, metals, and ceramics.

The response of industry representatives asked to review the preliminary findings of the survey was generally favorable. Much R&D related to NDT is ongoing at the federal laboratories, and NDT R&D is of obvious importance and interest to many in industry.

ACKNOWLEDGMENTS

This report is an account of work by Energetics, Inc., under subcontract no. B-K8583-A-V with Pacific Northwest Laboratory (PNL). PNL is operated under the continuing contract DE-AC06-76RLO 1830 for the U.S. Department of Energy. This study was initiated in July 1985 and completed in April 1986. PNL Program Manager was Ms. Nancy L. Moore, and PNL Project Manager was Mr. Steven A. Smith. Energetics' Project Manager was Mr. James E. Reed.

Numerous individuals contributed to this effort. They include:

Project Staff Members

Susan R. April
Jeff L. Conrad
Stan R. Edwards
Sharon J. Mannella

Project Consultants

Harold Berger
Charles R. Fink

Furthermore, much assistance was provided by laboratory personnel in arranging laboratory visits and interviews with principal investigators, in providing reports and other documents on NDT activities, and in reviewing draft technology descriptions. Their help is gratefully acknowledged. Thanks are also extended to industry representatives who reviewed a Preliminary Findings Report to assess the value of the information to industry.

CONTENTS

ABSTRACT	iii
SUMMARY	v
ACKNOWLEDGMENTS	xi
1.0 INTRODUCTION	1.1
1.1 BACKGROUND	1.1
1.2 METHODOLOGY	1.3
1.3 REPORT OBJECTIVES AND ORGANIZATION	1.7
2.0 OVERVIEW OF CURRENT NDT ACTIVITIES AND CAPABILITIES AT SELECTED FEDERAL LABORATORIES	2.1
2.1 AIR FORCE WRIGHT AERONAUTICAL LABORATORIES	2.1
2.2 AMES LABORATORY	2.2
2.3 ARGONNE NATIONAL LABORATORY	2.3
2.4 ARMY MATERIALS TECHNOLOGY LABORATORY	2.4
2.5 IDAHO NATIONAL ENGINEERING LABORATORY	2.4
2.6 LAWRENCE LIVERMORE NATIONAL LABORATORY	2.5
2.7 LOS ALAMOS NATIONAL LABORATORY	2.6
2.8 NASA LANGLEY RESEARCH CENTER	2.7
2.9 NASA LEWIS RESEARCH CENTER	2.8
2.10 NATIONAL BUREAU OF STANDARDS	2.9
2.11 OAK RIDGE NATIONAL LABORATORY	2.10
2.12 PACIFIC NORTHWEST LABORATORY	2.11
2.13 SANDIA NATIONAL LABORATORIES - ALBUQUERQUE	2.12
2.14 SANDIA NATIONAL LABORATORIES - LIVERMORE	2.13

3.0	FEDERAL LABORATORY NDT R&D AND FACILITIES APPLICABLE TO U.S. MANUFACTURING INDUSTRIES	3.1
3.1	ACOUSTIC EMISSION METHODS	3.2
3.1.1	A CONTINUOUS ACOUSTIC EMISSION MONITORING SYSTEM FOR FLAW DETECTION	3.3
3.1.2	ACOUSTIC EMISSION IN METALLURGY	3.7
3.1.3	ACOUSTIC EMISSION SOURCE LOCATION SYSTEM	3.9
3.1.4	NONDESTRUCTIVE EVALUATION OF TOOL WEAR AND CHIP FORMATION: ON-LINE SENSOR DEVELOPMENTS	3.12
3.2	EDDY CURRENT METHODS	3.14
3.2.1	ADVANCED EDDY CURRENT COIL EXCITATION AND SIGNAL PROCESSING	3.15
3.2.2	EDDY CURRENT EXAMINATION OF STEAM GENERATOR TUBES/SURRY STEAM GENERATOR FACILITY	3.18
3.2.3	EDDY CURRENT INSTRUMENTATION DEVELOPMENT	3.21
3.2.4	EDDY CURRENT INSPECTION RESEARCH	3.24
3.2.5	EDDY CURRENT JET ENGINE DISK-CRACK MONITOR	3.26
3.2.6	EDDY CURRENT PROBE DEVELOPMENT	3.29
3.2.7	EDDY CURRENT SENSORS FOR SMALL FLAW DETECTION IN METALLIC COMPONENTS	3.31
3.2.8	FMR ADVANCED SURFACE FLAW DETECTION METHODS	3.33
3.3	ELECTRICAL METHODS.....	3.35
3.3.1	CURE MONITORING IN POLYMERS VIA DIELECTRIC SPECTROSCOPY	3.36
3.3.2	MICROWAVE MEASUREMENT OF THE COMPLEX DIELEC- TRIC TENSOR OF ANISOTROPIC SLAB MATERIALS	3.40
3.4	MAGNETIC METHODS	3.41
3.4.1	FERROGRAPHY OF WEAR DEBRIS PARTICLES	3.42
3.4.2	INFLUENCE OF FATIGUE AND STRESS OF MAGNETIC PROPERTIES	3.43

3.4.3	MAGNETIC METHODS OF NONDESTRUCTIVE TESTING	3.44
3.5	RADIOGRAPHY AND RADIATION METHODS	3.46
3.5.1	DIRECT CONVERSION X-RAY IMAGING DETECTORS	3.47
3.5.2	DYNAMIC RADIOGRAPHIC IMAGING USING HIGH-SPEED VIDEO	3.48
3.5.3	HIGH AVERAGE POWER INDUCTION ACCELERATOR	3.50
3.5.4	HIGH-RESOLUTION NONFILM RADIOGRAPHY	3.51
3.5.5	LOW-ENERGY RADIOGRAPHY	3.53
3.5.6	MATERIALS CHARACTERIZATION WITH SMALL-ANGLE NEUTRON SCATTERING	3.55
3.5.7	MICROFOCUS ROD-ANODE X-RAY UNIT DEVELOPMENT AND APPLICATION	3.58
3.5.8	NBS CENTER FOR COLD-NEUTRON RESEARCH	3.60
3.5.9	RADIOGRAPHY AND COMPUTER TOMOGRAPHY CAPABILITIES	3.63
3.5.10	RADIOGRAPHIC DETECTABILITY LIMIT RESEARCH	3.64
3.5.11	RADIOGRAPHIC MATERIALS CHARACTERIZATION SYSTEM	3.67
3.5.12	RESEARCH INVESTIGATIONS IN INDUSTRIAL RADIOLOGY	3.70
3.5.13	RESIDUAL STRESS MEASUREMENTS WITH ENERGY DISPERSIVE X-RAY DIFFRACTOMETRY	3.72
3.5.14	TOMOGRAPHIC DENSITOMETRY	3.74
3.5.15	X-RAY TOMOGRAPHIC SYSTEM DEVELOPMENT	3.75
3.6	THERMAL METHODS	3.76
3.6.1	EARLY CORROSION DETECTION OF STEEL UNDER PROTECTIVE COATINGS USING THERMAL-WAVE IMAGING	3.77

3.6.2	THERMAL-WAVE IMAGING OF SURFACE AND NEAR-SURFACE DEFECTS IN CERAMICS	3.79
3.7	ULTRASONICS METHODS	3.81
3.7.1	ACOUSTOELASTIC MEASUREMENT OF STRESS AND TEXTURE	3.82
3.7.2	ADVANCED ULTRASONIC INSPECTION INSTRUMENT	3.84
3.7.3	AN AUTOMATIC ULTRASONIC DATA ACQUISITION SYSTEM	3.87
3.7.4	AN ULTRASONIC THICKNESS GAUGE	3.89
3.7.5	AUTOMATED MULTIVIEWING ULTRASONIC TRANSDUCER	3.91
3.7.6	AUTOMATED ULTRASONIC TEST BED	3.94
3.7.7	AUTOMATED WELDING NONDESTRUCTIVE EVALUATION	3.96
3.7.8	COMPUTER-AUTOMATED ULTRASONIC INSPECTION SYSTEM	3.97
3.7.9	CONCURRENT ULTRASONIC WELD INSPECTION	3.100
3.7.10	CRACK CHARACTERIZATION	3.101
3.7.11	EVALUATION OF EFFECTIVENESS OF HEAT TREATMENT ON STRENGTH OF ALUMINUM ALLOYS	3.102
3.7.12	FLAW CHARACTERIZATION WITH SCANNING LASER ACOUSTIC MICROSCOPY	3.104
3.7.13	FLAW DETECTION IN CONCRETE USING AN IMPACT-ECHO TECHNIQUE	3.106
3.7.14	FOCUSED REFLECTION ACOUSTIC MICROSCOPE	3.109
3.7.15	INTERNAL TEMPERATURE PROFILE OF HOT STEEL	3.112
3.7.16	NONDESTRUCTIVE EVALUATION DEVELOPMENT FOR COMPOSITE MATERIALS	3.113
3.7.17	NONDESTRUCTIVE EVALUATION OF COMPOSITE LAMINATES BY LEAKY LAMB WAVES	3.114
3.7.18	NONDESTRUCTIVE EVALUATION OF LAMINATED PANELS	3.116

3.7.19	NONDESTRUCTIVE EVALUATION OF INTEGRALLY FABRICATED TURBINE ROTORS	3.118
3.7.20	NONDESTRUCTIVE SYSTEMS FOR ON-LINE MONITORING OF EROSION WEAR	3.121
3.7.21	PHASE-INSENSITIVE TRANSDUCERS/COMPOSITE MATERIALS NONDESTRUCTIVE EVALUATION	3.122
3.7.22	PULSE-ECHO ACOUSTIC MICROSCOPY FOR INSPECTION OF SILICON CARBIDE COMPONENTS	3.125
3.7.23	PULSED PHASE LOCKED LOOP INTERFEROMETER	3.126
3.7.24	REAL-TIME, IN SITU, NONDESTRUCTIVE MONITOR- ING OF SOLIDIFICATION INTERFACES IN METALS	3.128
3.7.25	SPECIAL LOW-FREQUENCY TRANSDUCERS FOR CONCRETE INSPECTION	3.131
3.7.26	STANDARDS FOR ULTRASONIC MEASUREMENT OF RESIDUAL STRESS	3.133
3.7.27	STRESS LEVEL MEASUREMENT IN RAIL CAR WHEELS	3.135
3.7.28	SYNTHETIC APERTURE FOCUSING TECHNIQUE FOR ULTRASONIC IMAGING	3.138
3.7.29	ULTRASONIC AND ACOUSTIC EMISSION TRANSDUCER DEVELOPMENTS	3.141
3.7.30	ULTRASONIC CHARACTERIZATION OF POROSITY IN CAST ALUMINUM	3.143
3.7.31	ULTRASONIC EVALUATION OF CERAMIC AND RAPIDLY SOLIDIFIED ALLOY MATERIAL AND JOINTS	3.144
3.7.32	ULTRASONIC EVALUATION OF MATERIAL PROPERTIES	3.146
3.7.33	ULTRASONIC HIGH-SPEED DATA ACQUISITION SYSTEM	3.149
3.7.34	ULTRASONIC INSPECTION OF MATERIAL MICROSTRUCTURE	3.151
3.7.35	ULTRASONIC INSPECTION RESEARCH AND DEVELOPMENT	3.152
3.7.36	ULTRASONIC MEASUREMENT OF SURFACE ROUGHNESS	3.154

3.7.37	ULTRASONIC TESTING OF PLATES CONTAINING EDGE CRACKS	3.157
3.7.38	ULTRASONIC TOMOGRAPHY OF HOT METAL	3.159
3.8	VISUAL-OPTICAL METHODS	3.162
3.8.1	DIAGNOSTIC VIDEO PROBE FOR SEVERE ENVIRONMENTS	3.163
3.8.2	HIGH-SPEED INSPECTION SYSTEMS	3.164
3.8.3	LASER SURFACE MAPPER	3.167
3.8.4	OPTICAL MEASUREMENT OF SURFACE ROUGHNESS	3.168
3.9	OTHER METHODS	3.171
3.9.1	ASSESSMENT OF STRESS-CORROSION CRACKING IN DIGESTER VESSELS AND PIPING	3.172
3.9.2	EFFECT OF MATERIAL AGING ON NYLON 66 AND KEVLAR 29 STRENGTH DEGRADATION	3.174
3.9.3	EXPLORATORY RESEARCH AND DEVELOPMENT ON NONCONTACTING SENSORS	3.175
3.9.4	HEAVY-SECTION STEEL TECHNOLOGY PROGRAM	3.176
3.9.5	HOLOGRAPHIC AND REAL-TIME IMAGING SYSTEMS	3.177
3.9.6	MICROPENETRATION INSTRUMENT	3.180
3.9.7	NONDESTRUCTIVE EVALUATION DEVELOPMENT FOR CERAMIC MATERIALS	3.181
3.9.8	NONDESTRUCTIVE EVALUATION DEVELOPMENT FOR LIGHT-WATER REACTORS	3.182
3.9.9	NONDESTRUCTIVE EVALUATION FOR HEAT ENGINE CERAMICS	3.184
3.9.10	NONDESTRUCTIVE EVALUATION OF ACID RAIN DAMAGE TO MATERIALS	3.188
3.9.11	NONDESTRUCTIVE EVALUATION OF ADVANCED CERAMIC COMPOSITE MATERIALS	3.190
3.9.12	NONDESTRUCTIVE EXAMINATION OF CERAMIC MATERIALS	3.191

3.9.13 NONDESTRUCTIVE EXAMINATION OF GRAPHITE MATERIALS	3.193
4.0 INDUSTRY REVIEW	4.1
5.0 CONCLUSIONS AND RECOMMENDATIONS	5.1
5.1 CONCLUSIONS	5.1
5.2 RECOMMENDATIONS	5.2
APPENDIX A - POTENTIAL APPLICATIONS OF FEDERAL LABORATORY NDT ACTIVITIES IN U.S. MANUFACTURING INDUSTRIES.....	A.1
APPENDIX B - RESOURCES AND OPPORTUNITIES IN NDT RESEARCH	B.1

FIGURES

3.1	Functional Diagram of Engineering Prototype AE Monitoring System	3.4
3.2	Schematic Diagram of AE Source Location Module	3.11
3.3	Simplified Block Diagram of Crack Monitoring Sensor	3.27
3.4	Block Diagram of NBS Time Domain Dielectric Spectrometer	3.37
3.5	Schematic Diagram of Apparatus Used for Small-Angle Scattering Experiments	3.55
3.6	Geometry of Current NBS Cold-Neutron Source	3.61
3.7	Conventional Contact Radiography and Projection Microfocus Techniques	3.65
3.8	Materials Characterization System at LLNL	3.68
3.9	Data Flow Diagram for Materials Characterization System	3.69
3.10	Block Diagram of Test Points in Typical Ultrasonic Instrument	3.85
3.11	Pulse-Echo Method for Flaw Detection in Concrete	3.107
3.12	Experimental Geometry of Lamb-Wave Measurements in Fibrous Composite Plates	3.115
3.13	Sample Geometry of Ring-Plug Configuration and Residual-Stress Profile for the Principal Stress Difference According Elasticity Theory	3.134
3.14	Experimental Configuration of a Transducer Operating as Both a Transmitter and Receiver, Relative to a Steel Sample for Successive Echo Amplitude Measurements	3.155
3.15	Ultrasonic Velocity Tomography Measurements in Hot Steel at NBS	3.161
3.16	Eddy Current Phasography and Focused Probe Imaging System	3.178

TABLES

S.1	Laboratories Surveyed	vi
1.1	Comparison of Common NDT Methods	1.4
1.2	Laboratories Surveyed	1.6

1.0 INTRODUCTION

Federal laboratories are chartered with missions pertaining to energy, space, defense, and other technology areas of national interest. Each of the more than 700 federal laboratories is maintained as a center of excellence in one or more highly focused technical areas. The primary users of the work conducted in the laboratories are similarly specialized groups.

Federally funded technology and laboratory capabilities can be of critical value to the private industrial sector, especially when they present opportunities for improving energy efficiency and the overall productivity of industrial processes. Federally funded technology can remain relatively unknown in private industry, however, if the technology is developed for an unrelated area or the time and resources required to identify and analyze its applications are prohibitive.

1.1 BACKGROUND

The need for full and effective use of federally funded research, development and demonstration has been addressed by many. For example, in May 1983 The President's Federal Laboratory Review Panel issued the results of a comprehensive study of ways to better use the great potential of the laboratories (Office of Science and Technology Policy 1983). This study focused on the interaction of the federal laboratories with universities, industry, and users of research results. Major recommendations were that:

"Federal laboratories should encourage much more access to their facilities by universities and industry."

R&D interactions between federal laboratories and industry should be greatly increased by more exchange of knowledge and personnel, collaborative projects, and industry funding of laboratory work ..."

The Congress has similarly recognized a need to stimulate more effective utilization of federally funded technology by the private sector. The Stevenson-Wydler Technology Innovation Act of 1980 (P.L. 956-480) established a continuing responsibility of the federal government to ensure full use of the results of the nation's investment in research and development (R&D). The Act

requires each federal laboratory with a budget exceeding \$20 million to provide at least one full-time professional staff member to fulfill the role of a Technology Utilization Officer (TUO). The TUO cooperates with and assists organizations that link the resources of the laboratory to potential users in private industry.

Three previous surveys of federally developed technology have shown that there is value in the direct transfer of such information to private industry. The previous surveys were 1) a survey of federal laboratory R&D applicable to the pulp and paper industry (Moore 1983), 2) a survey of materials R&D in federal laboratories applicable to six manufacturing industries (Moore 1984), and 3) a survey of the U.S. Department of Defense Manufacturing Technology Program to identify activities applicable to civilian general manufacturing and primary metals industries (Moore 1985). These surveys concluded that the information retrieved and transferred to industry was valuable to industry and that many of the technologies were previously unknown.

This report presents the results of a survey of selected federal laboratories to identify nondestructive testing (NDT) and related sensor technology R&D of potential use within the entire range of manufacturing industries. The objective of this report is to provide a resource for the manufacturing industries [i.e., Standard Industrial Classifications (SICs) 20 through 39] listing federally funded R&D activities that can promote energy efficiency or overall productivity improvements within their industries.

As a preliminary note, it is worthwhile to clarify the terminology used in this report. Several terms refer to methods for detection and measurement of discontinuities or anomalies in materials, components, or assemblies by tests that do not impair the serviceability of the tested object. These include nondestructive testing (NDT), nondestructive evaluation (NDE), nondestructive inspection (NDI), and nondestructive examination (NDE). A report by the National Materials Advisory Board (1977) recommends the following set of definitions:

- Nondestructive testing (NDT) is used in a basic or generic sense to describe testing methodology or to define the general application of nondestructive testing principles.

- Nondestructive inspection (NDI) refers to the performance of the inspection to meet an established specification or procedure whether during fabrication or during service.
- Nondestructive evaluation (NDE) refers to the examination of Materials, components, and assemblies conducted to define and classify material anomalies in terms of size and type and position.

Within this report, no attempt was made to distinguish between these various terms. When discussing the project in general, the term NDT will be used; when discussing a specific laboratory, the terminology of that laboratory will be used. Generally, the terms NDT and NDE are interchangeable; sensor technology refers to NDT-related sensors.

NDT technologies have tremendous potential for increasing the productivity of materials, energy, and labor in product manufacture and throughout product lifetime. In areas such as quality control, process control and safety, detecting the characterizing defects or anomalies (or the characterizing material properties) without destroying the subject or taking it out of service is extremely useful.

NDT has emerged as a distinct discipline encompassing a range of testing methods. Among the more common NDT methods are ultrasonics, radiography, eddy currents (EC), visual-optical, liquid penetrant, and magnetic particles. Each method has its characteristic advantages, limitations and uses. Table 1.1 provides a comparison of common NDT methods. Because of the many benefits and uses of NDT technologies, considerable R&D is conducted at several federal laboratories related to their specific energy, defense or space-related missions.

1.2 METHODOLOGY

The principal steps in this effort are listed below:

- identify the federal laboratories, programs and staff conducting NDT and sensor technology R&D potentially applicable to industry
- contact the laboratories to survey and categorize relevant R&D

TABLE 1.1. Comparison of Common NDT Methods

Method	Characteristics Detected	Advantages	Limitations	Examples 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 either by contact to surface or immersion in a fluid; orientation can present problems in detection or interpretation of defect.	Adhesive assemblies for bond integrity; detection of cracks.
Radiography	Changes in material density caused by voids, inclusions, material variations; placement of internal parts.	Can be used to inspect wide range of materials and thicknesses; versatile; film provides records of inspection.	Radiation safety requires precautions; expensive; detection of cracks can be difficult.	Pipeline welds for penetration, inclusions, voids; verification of parts in assemblies.
Eddy Currents	Changes in electrical conductivity or magnetic permeability caused by material variations, cracks, voids, or inclusions.	Readily automated; moderate cost.	Limited to electrically conducting materials; limited penetration depth; interpretation of defect signals can be difficult.	Heat exchanger tubes for wall thinning and cracks; verification of material heat treatment.
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.
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; detection of weld defects.

- analyze the candidate technologies identified to determine in what industries and process steps they might apply
- review findings with industry representatives and prepare a final report.

As a first step in the survey, the federal laboratories active in NDT technologies R&D were identified, including the specific divisions and staff. This was accomplished through various means including:

- reviews of previous federal laboratory surveys
- published directories of federal laboratory capabilities and resources
- recommendations by project consultants familiar with federal laboratory missions and staff
- contacts with laboratory Technology Utilization Officers or appropriate technology transfer contacts.

Ultimately, a list of laboratories was assembled, from which thirteen were selected for more detailed treatment on the basis of potential value of their work to industry. Although required to survey six laboratories (three by visits and three by mail and telephone inquiries), a total of thirteen laboratories were surveyed (eight through visits and five through mail and telephone inquiries) to ensure good coverage of federal laboratory NDT work. Laboratories surveyed are listed in Table 1.2.

The next step was to contact the TUO and department or division head(s) responsible for NDT work at each laboratory. After the project's purpose and scope were described, materials discussing NDT activities were requested and arrangements were made to visit the selected laboratories. Laboratory visits typically involved overviews of NDT work and tours of laboratory facilities followed by interviews with individual principal investigators responsible for specific work efforts. For the laboratories not visited, materials received were screened to identify activities of interest.

The formatted descriptions of laboratory NDT activities contained in this report were prepared using all available information, including project

TABLE 1.2. Laboratories Surveyed

Laboratories Visited

1. Air Force Wright Aeronautical Laboratories (AFWAL)
2. Lawrence Livermore National Laboratory (LLNL)
3. Los Alamos National Laboratory (LANL)
4. NASA Langley Research Center (LaRC)
5. NASA Lewis Research Center (LeRC)
6. National Bureau of Standards (NBS)
7. Pacific Northwest Laboratory (PNL)
8. Sandia National Laboratories (SNL)

Laboratories Surveyed by Mail and Telephone

1. Ames Laboratory (Ames)
2. Army Materials Technology Laboratory (MTL)
3. Argonne National Laboratory (ANL)
4. Idaho National Engineering Laboratory (INEL)
5. Oak Ridge National Laboratory (ORNL)

reports, technical papers, program summaries, and trip reports containing interview notes. Due to the expanded scope of the survey, descriptions were written with the material available; therefore, the level of detail of the descriptions may vary. To verify the accuracy of the descriptions, they were sent to the appropriate laboratory section or division head for review, and the descriptions were revised as necessary.

Although efforts were made to include only up-to-date information and to ensure the accuracy of the information, technical programs and projects are in a constant state of flux, and thus the information presented is subject to change. Also, the work described in this report is in no way intended to represent all of the NDT-related work conducted by federal laboratories or even all of the NDT work at the laboratories surveyed. Instead, the objective is to describe some of the current NDT activities and capabilities at these laboratories that are of potential interest to industry.

After the descriptions were completed, potential industrial applications of NDT activities were identified and expanded upon as possible. Although the

exercise was not a detailed or exhaustive analysis of possible use of the technologies, it represents a useful first step in coupling the work described to further applications in U.S. manufacturing industries. A liberal approach was used to determine applicability. Therefore, applicability may be direct or indirect, immediate or far in the future.

The next step was to review the findings of the survey with industry representatives. The descriptions, arranged according to NDT method, were compiled in a Preliminary Findings Report and distributed to fifteen people in industry who represent a range of manufacturing industries, along with a letter requesting comments. This final report was prepared to summarize the overall results.

1.3 REPORT OBJECTIVES AND ORGANIZATION

The purpose of this report is to present the findings of the survey of NDT technology R&D at selected federal laboratories. Section 2.0 presents brief overviews of current NDT activities and capabilities at the federal laboratories surveyed. Section 3.0 describes NDT R&D, organized by NDT method. Section 4.0 outlines industry review comments on the preliminary findings of the survey, and Section 5.0 provides relevant conclusions and recommendations. Appendix A lists potential industrial applications of NDT technology. Appendix B discusses some resources and opportunities for NDT research of possible interest to industry. Finally, Appendix C includes a cross-index of the projects, listed by laboratory, and a keyword index.

REFERENCES

"Federal Laboratory Report," Office of Science and Technology Policy, Executive Office of the President, Washington, DC, May 1983.

Moore, N. L. 1985. Survey of U.S. Department of Defense Manufacturing Technology Program Activities Applicable to Civilian Manufacturing Industries. PNL-5466, Pacific Northwest Laboratory, Richland, Washington.

Moore, N. L. 1984. Survey and Analysis of Materials Research and Development at Selected Federal Laboratories. PNL-5061, Pacific Northwest Laboratory, Richland, Washington.

Moore, N. L. 1983. Survey and Analysis of Federally Developed Technology.
PNL-4499, Pacific Northwest Laboratory, Richland, Washington.

National Materials Advisory Board. "Economic and Management Aspects of Nonde-
structive Testing, Evaluation and Inspection in Aerospace Manufacturing."
Report NMAB-337, National Academy of Sciences, Washington, DC (1977).

2.0 OVERVIEW OF CURRENT NDT ACTIVITIES AND CAPABILITIES AT SELECTED FEDERAL LABORATORIES

This section summarizes the focus and range of NDT activities and capabilities at the federal laboratories surveyed. It also identifies several items of potential interest to industry for present or future technology transfer. Contacts at each laboratory are also provided.

2.1 AIR FORCE WRIGHT AERONAUTICAL LABORATORIES (AFWAL)

Contacts: J. Moyzis (R&D Group)
AFWAL/MLLP
Wright Patterson AFB, OH 45433
(513) 255-5309

D. T. Cooper (Systems Area)
AFWAL/MLSA
Wright Patterson AFB, OH 45433
(513) 255-2623

L. Gulley (MANTECH Program)
AFWAL/MLTM
Wright Patterson AFB, OH 45433
(513) 255-2413

Several centers for NDE R&D exist at AFWAL related to different aspects of AFWAL's mission. NDE work is conducted by the Nondestructive Evaluation Branch that focuses primarily on R&D, by the Support Services Branch that represents systems and inspections at depots of Air Logistics Centers, and as part of the U.S. Department of Defense (DOD) Manufacturing Technology Program. Work by the different groups is often related and much of it is conducted through contractors.

NDE work at AFWAL encompasses a wide range of methods and applications. Work by the R&D group includes composite curing R&D using ultrasonic and fluorescence techniques (by McDonnell Douglas in St. Louis); real-time radiography work on improved x-ray to light converters (by Lockheed and SAI); a hand-scan UT system called Automated Real-Time Inspection System (ARIS) for composites NDE; and large area composite inspection using a Mobile Automated Ultrasonic Scan (MAUS) system (developed at McDonnell Douglas).

Some NDE work is performed in the Systems Area including the evaluation of new NDT equipment (both Air Force-developed and other), the development of specifications and standards, and the monitoring of R&D programs. Equipment evaluated includes a PNL-developed ultrasonic instrument and an EC instrument for detecting cracks around fasteners being evaluated at Systems Research Laboratory. In the specifications area, the Systems staff set the rules for the Qualified Products List (QPL) for liquid penetrants; manufacturers must get their products on the list to sell to the military (and many other industrial customers).

Important NDE work under the Manufacturing Technology (MT) Program includes the integrated blade inspection system (IBIS) being developed by General Electric involving x-ray and infrared turbine blade inspection, computerized tomography work at Aerojet and ARACOR, and an EC scanning system to detect small cracks in engine discs as part of a retirement-for-cause program.

2.2 AMES LABORATORY (Ames)

Contact: D. O. Thompson
225 Applied Sciences Center
Ames Laboratory - Iowa State University
Ames, Iowa 50011
(515) 294-7803

A wide range of NDE research is pursued at Ames from fundamental solutions to practice (one-of-a-kind prototypes). NDE work is a key building block of a broader Ames thrust in Materials Reliability. Work is done under both public funds and private contracts from industry.

Major NDE efforts at Ames are funded by the Office of Basic Energy Sciences, U.S. Department of Energy (DOE) and by the Materials Laboratory, AFWAL. Basic Energy Sciences support comes from both the Engineering Sciences and Metallurgy and Ceramics groups. Ames manages the Interdisciplinary Program for Quantitative Nondestructive Evaluation sponsored by AFWAL. The Air Force work is centered at Ames, but much of the work is subcontracted to other NDE investigators throughout the country. Ames is also closely connected to the

Center for NDE at Iowa State University, an Industry/University Cooperative Research Center jointly funded by industry, the university and the National Science Foundation.

Ultrasonic techniques are a focus of NDE efforts. Examples include development of an automated multiprobe ultrasonic transducer and associated signal processing software, theoretical work on ultrasonic characterization of porosity in cast aluminum, and theoretical work and capabilities in the area of stress measurement.

2.3 ARGONNE NATIONAL LABORATORY (ANL)

Contact: K. J. Reimann
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439
(312) 972-5008

NDE research at ANL is conducted by the Nondestructive Evaluation and Failure Analysis Group of the Materials Science and Technology Division. The Group is relatively small (less than ten persons) and includes five full-time researchers and two visiting scientists.

Current NDE and failure analysis efforts (in support of materials research) are aimed at the following areas:

- characterizing materials, especially ceramics, during various stages of processing
- evaluating the structural integrity of materials in large components of energy conservation systems
- pinpointing causes and remedies for improper component behavior
- establishing deterioration rates of materials, especially stone, caused by acid rain.

These tasks are generally parts of larger programs, some of which are shared by other laboratories according to national plans, and some of which have evolved from problems encountered in operating plants. The programs

pursued by the Group address specific problems in support of fossil energy conversion systems, nuclear reactors, and evaluation of damage caused by acid rain.

2.4 ARMY MATERIALS TECHNOLOGY LABORATORY (MTL)

Contact: A. L. Broz
Attn: SLCMT-MSI-NE
U.S. Army Materials Technology Laboratory
Arsenal Street
Watertown, MA 02172
(617) 923-5250

The MTL, formerly the Army Materials and Mechanics Research Center (AMMRC) conducts the Army's materials R&D program as designated by the U.S. Army Material Command (AMC).

The Nondestructive Evaluation (NDE) Branch of MTL's Materials Testing and Evaluation Division provides a full service capability in NDE to AMC's commands, subcommands, program managers, engineers, fabricators, failure analysts and contractors. Programs cover the spectrum from basic studies applicable to testing to applied and developmental research and manufacturing technology. The NDE branch also develops procedures and documentation for contractor's inspections and specification of materials for processing and manufacturing.

The NDE branch has expertise and facilities in ultrasonics, magnetic particle, liquid penetrant, electromagnetics, magnetic flux leakage, EC, x-radiography and infrared imaging. MTL is the site of an NDT training school that provides a variety of training courses and other NDT services to the Army and other service organizations. The DOD NDE Specifications and Standards Program is also managed by MTL.

2.5 IDAHO NATIONAL ENGINEERING LABORATORY (INEL)

Contact: J. A. Seydel
Idaho National Engineering Laboratory
EG&G, Idaho
P.O. Box 1625
Idaho Falls, ID 83415
(208) 526-6000

NDE work at INEL focuses primarily on ultrasonics, but some work is also under way in EC, radiography, optical and other methods. Work is supported by various agencies including the DOE's Offices of Basic Energy Sciences and Industrial Programs, the Bureau of Mines (BOM) at the Department of the Interior, and the Department of Transportation. Currently, the largest program is for the BOM; the work involves the ultrasonic examination of material microstructure so that superior mineral production processes can be developed and substitutes for various strategic materials can be perfected.

2.6 LAWRENCE LIVERMORE NATIONAL LABORATORY (LLNL)

Contact: R. Streit
University of California
Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, CA 94550
(415) 422-7045

The mission of the Nondestructive Evaluation Section at LLNL is to provide a national resource in advanced NOE, with special attention to national security matters. The section (consisting of about 35 people) develops NDE techniques to assist weapons production facilities and other organizations within LLNL. Major facilities being built/developed at LLNL include fusion systems and advanced lasers. The work of the section is about 50% devoted to programs (meeting needs of in-house and production facility programs), 20% to maintaining capabilities and equipment and 15% each to development (upgrade of existing capability) and research (new projects funded by the LLNL Director).

The technical work includes application of liquid penetrants and magnetic particles (including safety-related inspections of fork lifts and crane hooks), some prior work in holography, and extensive current work in application and R&D in radiation and ultrasonic techniques.

The radiation work includes radiography with x-rays in the energy range 3 keV to 11 MeV (LLNL has a truck-mounted 11 MeV linear accelerator for field work and several other, lower-energy MeV-range machines), electron radiography, tomography, scatter techniques (Compton scatter, beta scatter) and gauging.

Most of the radiation inspection results can be presented in a digitized, image format through a computer imaging and analysis system.

A major facility at LLNL is an ultrasonic test bed that provides a 14-independent-degrees-of-freedom manipulation system, and a special tubing inspection system to examine tubing with wall thicknesses as small as 0.003 inch and diameters as small as 0.1 inch. In addition, LLNL has a focused beam reflection-mode acoustic microscope that operates in the frequency range of about 10 M to 100 MHz.

Items to be emphasized for technology transfer purposes include the acoustic microscope, ultrasonic test bed, image processing for radiography, low-energy x-ray capability, and quantitative radiation test capability. Signal processing software is thought to be of most value and interest to industry.

2.7 LOS ALAMOS NATIONAL LABORATORY (LANL)

Contact: T. Feiertag
MS C 914
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, New Mexico 87545
(505) 667-6291

Nondestructive testing work at LANL supports the primary mission of the laboratory, but additional contract or outside work is performed using equipment developed as part of the LANL mission. Five engineers and three to four technicians make up the NDT R&D staff. The majority of work is concentrated in radiography (x-ray, gamma and neutron). Other capabilities in ultrasonics and EC, are used for routine examinations, and no developmental work is currently being pursued.

Two major activities are under way at LANL. The first involves developing an x-ray tomographic system for flaw characterization and density gauging. The second effort is in applying their real-time, dynamic, optical, and radiographic imaging system to new applications. The new technologies associated

with these developments are primarily in software to control the systems operation and in selecting subsystems for image enhancement.

2.8 NASA LANGLEY RESEARCH CENTER (LaRC)

Contact: J. Heyman
NASA Langley Research Center
Bldg. 1230, Room 135
Hampton, VA 23665
(804) 865-3036

The Laboratory for Materials Characterization Instrumentation at LaRC is the lead center for long-range research in NDE for NASA. The Laboratory has a working staff of about 24, half of which are at the Ph.D. level. The NDE research program focuses on applied physical acoustics, emphasizing composite materials and special aspects of material state in metals. NDE efforts are directed mainly toward the development of advanced NDE techniques, procedures and equipment that can be used to characterize more accurately the physical properties or state of materials. Studies and investigations of nonlinear behavior have been a focal point of activities.

An objective of these measurements and assessments of the condition of engineering materials is to predict more accurately the failure rates (remaining life) of these materials in structures. Three parameters are studied with equal emphasis: stress, material property, and flaw size. These areas are further broken down into other measurable characteristics such as aging, fatigue, stress change, and new or old flaw growth. Subtle areas such as the migration of dislocations are also considered.

An example of composites NDE is the development of an acoustic power detector insensitive to phase variation that is capable of superior resolution in composites and capable of early detection of fatigue damage. Acoustic scattering measurements have also been conducted that have promise for practical ultrasonic imaging of separate lamina damage. In metals NDE, techniques have been developed to determine applied and residual stresses, many based on an ultrasonic phase locked loop instrument developed at LaRC.

2.9 NASA LEWIS RESEARCH CENTER (LeRC)

Contact: A. Vary
MS 23-3
NASA Lewis Research Center
Cleveland, OH 44135
(216) 433-6019

The Structural Integrity Branch at LeRC, a center for NDT work, consists of about 15 people (engineers, physicists, mathematicians and material specialists). The major emphasis in NDT is related to materials development in support of the propulsion-related mission at LeRC. The NDT effort is mainly the characterization of materials including ceramics, metals, polymers and composites. Work is also under way on defect detection and characterization, particularly in ceramics, the major materials focus.

LeRC collaborates extensively with universities, including a research program in composites at the Virginia Polytechnic Institute and the Massachusetts Institute of Technology, and an extensive cooperative program with Cleveland State University. Plans include additional efforts with the NDE Centers at the Johns Hopkins and Iowa State Universities and with the University of Cincinnati (NMR work). There have been joint efforts in ceramics with ANL and ORNL. At ORNL, LeRC supports NDE in ceramic monolithics (SiN, SiC) and ceramic composites.

LeRC offers opportunities for industrial interactions; for example, LeRC and engine manufacturers (including Allison, Ford and Garrett) have worked closely together. Permission can be obtained for industrial personnel to work with LeRC either in a collaborative mode or to use LeRC laboratory equipment. Equipment of interest for NDT researchers includes a Tektronix waveform analyzer 719AD coupled to a PDP1134 for ultrasonic attenuation measurements, a Grinnell image processor and PDP1184 for image analysis, a Nicolet microfocus x-ray unit with both film and real-time detection and a Scanning Laser Acoustic Microscope (SLAM), by Sonoscan.

Ultrasonic measurements are emphasized, as related to material properties, particularly important mechanical properties such as toughness. A wide range

of ultrasonic measurements have been studied. Work has been reported in composites, metals, and ceramics using ultrasonics, acoustic microscopy and radiography.

2.10 NATIONAL BUREAU OF STANDARDS (NBS)

Contact: L. Mordfin
National Bureau of Standards
Office of NOE
Washington, DC 20234
(301) 921-3331

The goal of the NBS NDE program is to improve productivity and product quality in American industry by encouraging the use of advanced NDE methods during materials processing, manufacturing and in-service inspection.

The overall objectives of the NBS program over the next five years include four broad items, as follows:

- science: provide the scientific understanding needed to develop NDE measurement methods and standards traceable to national standards
- standards: develop, provide and promote effective standards for obtaining and verifying accurate NDE measurements to enhance compatible and quantitative NDE during materials processing, manufacturing, and in-service inspection
- measurement methods: develop generic approaches, sensors, and procedures for quantitative NDE and relate these to the properties of materials and manufactured parts and structures
- national focus: provide a forum to develop and foster a national strategy that will advance and utilize NDE to increase the United States' industrial competitiveness.

The resources available for these purposes include a broad-based scientific staff, excellent facilities, and financial support of about \$2.8 million.

From the standpoint of technology transfer, cooperative programs with NBS are possible. The Research Associate program, for instance, enables industry

to place research workers at NBS to conduct research in areas of mutual interest with NBS scientists and engineers. NBS furnishes office, laboratory and professional support, and industry supports the person or persons they place at NBS. The research results of this program are normally made available through joint publication. Presently there are about 200 Research Associates at NBS with approximately six working in areas associated with NDE.

NBS can work with industry to perform proprietary research, which is a new capability for the federal laboratories. Industries desiring additional information in this area should contact the NBS Office of NDE directly. Industry may arrange to use NBS facilities on a time/cost basis. This is generally limited to cases in which NBS has some unique equipment/facility.

The NBS NDE program includes many activities in a broad range of NDE disciplines. The total program is described in the NDE annual reports.

2.11 OAK RIDGE NATIONAL LABORATORY (ORNL)

Contact: R. W. McClung
Metals and Ceramics Division
Oak Ridge National Laboratory
P.O. Box X
Oak Ridge, TN 37831
(615) 574-4466

The Nondestructive Testing Group at ORNL develops new and improved techniques and equipment for NDE of materials and components, including metal, ceramic, composite, and carbon materials. The range of activities includes: 1) theoretical studies and mathematical modeling, 2) design and development of instrumentation, sensors, and mechanical equipment, 3) development of new or modified techniques and procedures (including reference and calibration standards), and 4) transfer of technology to interested users. The NDT Group is multidisciplinary with nine full-time personnel, a consultant, part-time employees (from the faculties of Ohio State University and the University of Tennessee), and assigned craft personnel.

NDT work focuses on penetrating radiation, EC and ultrasonic methods. Penetrating radiation methods (using x-rays, gamma rays, and neutrons) have

included both qualitative imaging (radiography and image enhancement with conventional, low-voltage, and microradiographic techniques) and quantitative measurements. Electromagnetic induction EC work features computer design for optimized techniques and instruments, for example, a multiparameter instrument. Ultrasonic development covers all facets from applications development to innovative signal processing emphasizing ultrasonic spectroscopy, time deconvolution, and other techniques for quantitative flaw characterization. In addition, advanced thermal methods have been developed and applied in several projects. Other areas of experience are liquid penetrants, microwave, optics, holography, x-ray fluorescence, acoustic emission, leak testing, and electrochemical techniques. Activities have included quantitative flaw detection and characterization in welds and other fabrication materials and components, and studies for determining material properties beyond flaw detection.

2.12 PACIFIC NORTHWEST LABORATORY (PNL)

Contact: G. J. Posakony
Pacific Northwest Laboratory
P.O. Box 999
Richland, WA 99352
(509) 375-2372

At PNL, NDT work is conducted both as part of a DOE mission to support nuclear activities at Hanford and as part of R&D assignments from other government agencies and from industry. NDT work is concentrated in the NDT Section (about 40 people) and in the Electro-Optic Systems Section (about 30 people). A mission of the NDT Section is to advance concepts from the research stage to the engineering phase to make the technology more attractive to industry.

In broad terms, PNL has technology for acoustic emission (AE) monitoring; inspection equipment and transducers involving ultrasonics and EC; high-speed dimensional measurements and surface inspections; imaging techniques for ultrasonics, EC, microwaves, and gamma rays; and reliability and round robin techniques and analyses.

Because a mission at PNL is primarily to move R&D concepts along to the engineering stage, many of its activities are appropriate (and essentially

ready) for technology transfer. For some of the technology reported here, the technology transfer process is already under way, specifically the ultrasonic instrument developed for the Air Force (now being offered commercially by Nortec) and the synthetic aperture focusing technique work (to be eventually commercialized by Combustion Engineering).

PNL has collected extensive data on NDT equipment, particularly ultrasonic equipment. Evaluations have been discussed with many equipment manufacturers with positive results. PNL staff is also active in the area of codes, regulations, and standards with organizations such as the American Society for Testing and Materials (ASTM), the American Society for Mechanical Engineers (ASME), and the U.S. Nuclear Regulatory Commission (NRC).

2.13 SANDIA NATIONAL LABORATORIES - ALBUQUERQUE (SNL-A)

Contacts: W. W. Shurtleff	O. J. Burchett
Nondestructive Testing	Nondestructive Testing
Technology Division 7552	Technology Division 7551
Sandia National Laboratories	Sandia National Laboratories
Albuquerque, NM 87185	Albuquerque, NM 87185
(505) 844-3500	(505) 844-3500

The NDT R&D staff at SNL-A is divided into two divisions. Division 7551, under the direction of O. J. Burchett, has the responsibility for radiographic developments. Division 7552, under the direction of W. W. Shurtleff, has the responsibility for ultrasonics, AE, and high-speed data acquisition. There are 12 to 15 technical staff in the NDT divisions at SNL-A.

Although SNL-A is active in technology transfer within the weapons laboratories, transfer outside the weapons laboratories is limited by staff availability and contractual procedures that would permit access to new development.

Areas of NDE work include radiography (real-time radiography, flash radiography and computed tomography) ultrasonics, AE, and data acquisition systems development.

2.14 SANDIA NATIONAL LABORATORIES - LIVERMORE (SNL-L)

Contact: A. R. Willis
Acceptance Technology Division
Sandia National Laboratories
Livermore, CA 94550
(415) 422-2641

The Acceptance Technology Division at SNL-L has three main functions:

1) performing NDE of weapon development hardware and facility hardware,
2) developing new NDE technology, some of which may be transferred to weapons production facilities, and 3) providing product acceptance liaison with the weapon production facilities for SNL-L designed components and systems. For the last function, this division shares responsibility with the SNL-L project engineering and quality assurance organizations for reviewing and approving product acceptance techniques and procedures used by the production facilities. The division is relatively small, with fewer than 10 people in NOE. The division is very well equipped so that the staff can provide timely response to a wide variety of NDE problems on complex development hardware and also respond to critical production problems.

Current R&D programs with technology transfer potential include:

- developing NDE technology for evaluating solid-state welds, emphasizing computer-based ultrasonics techniques with sophisticated software for signal processing, image analysis and data presentation
- developing micro-focus, real-time radiography and film techniques for evaluating small components and studying functions of components
- developing computer-based precision radiation gauging capabilities.

3.0 FEDERAL LABORATORY NDT R&D AND FACILITIES APPLICABLE TO U.S. MANUFACTURING INDUSTRIES

This section describes those NDT activities and facilities identified during this survey that are potentially applicable to improving energy efficiency and productivity in U.S. manufacturing industries (SICs 20 through 39). Descriptions include:

- technology (or project) name
- federal laboratory performing or supporting the work
- name, title, and telephone number of the principal contact(s)
- summary description of the work
- reference materials, if available.

The descriptions are organized according to the following NDT methods:

- acoustic emission
- eddy currents
- electrical
- magnetic methods
- radiography and radiation methods
- thermal
- ultrasonics
- visual-optical
- others.

The "others" category includes efforts directed at a particular material or addressed to a particular problem and encompasses more than one NDT method.

3.1 ACOUSTIC EMISSION (AE) METHODS

3.1.1 A CONTINUOUS ACOUSTIC EMISSION MONITORING SYSTEM FOR FLAW DETECTION

Laboratory: Pacific Northwest Laboratory (PNL)

Contact: Phil H. Hutton
Nondestructive Testing Section
(509) 375-2157

A major program at PNL is directed at developing AE methods for continuous monitoring and evaluation of flaw growth in reactor pressure vessels (Hutton and Kurtz 1985). Industrial pressure containment systems are often subject to failure during operation; however, the normal operating environment (especially in nuclear systems) precludes regular inspection except during shutdown. PNL has developed an AE instrument system capable of continuously monitoring flaws in the reactor environment. A functional diagram of the prototype system is shown in Figure 3.1.

National codes and federal regulations specify the type and frequency of in-service inspections that must be performed to detect unsafe cracking conditions in reactor pressure vessels. Thus far, only two methods have been certified for such inspections: radiography and ultrasonic testing. PNL, in conjunction with the NRC, is looking to AE monitoring as an alternative, and possibly superior, inspection method.

When flaws or cracks grow, minute amounts of elastic energy are released and propagate through the materials as acoustic waves. AE monitoring detects these waves through specially designed sensors. PNL's system uses pressure-sensitive sensors with piezoelectric ceramic elements. The element transforms elastic-wave energy into electrical signals.

The PNL-designed sensor also has the unique capability to be direct mounted on a high-temperature surface (500°F to 600°F). A stainless steel rod equipped with metal waveguides (0.130 inch diameter) is pressure mounted to the hot surface; a piezoelectric sensing element (PZT5A) and a preamplifier are integrated into a compact package located at the other end of the rod. The sensor assembly can thus be removed from the waveguide to protect it from damage during construction activity. The ability to quickly exchange a sensor,

FIGURE 3.1. Functional Diagram of Engineering Prototype AE Monitoring System (Hutton and Kurtz 1985)

should one fail during active service, is extremely important in terms of personnel exposure time as well as overall cost.

Researchers at PNL are investigating computer-aided signal pattern recognition techniques to discriminate AE signals produced by crack growth from those produced by innocuous sources (e.g., pump operation, thermal expansion and cooling, etc.). During initial testing, a three-pulse signal pattern was found in practically all waveforms originating near known and suspected regions of crack growth. It was determined experimentally that these three pulses are actually wave modes that had been separated in the waveguides as a response to high-frequency, short-duration input pulses, i.e., AE signals. Therefore, the transmissions properties of the waveguides could be used to discriminate AE signals. Work is progressing on incorporating pattern recognition techniques into the prototype system so that acoustic signals can be analyzed as they are received (Hutton and Kurtz 1985).

The prototype AE system is currently being used to monitor an inlet weld nozzle at TVA's Watts Bar Nuclear Reactor. The system has been highly successful in monitoring and predicting crack growth for planar flaws; however, the extent of more complicated cracks tends to be over-predicted. Background noise interference (e.g., from reactor coolant flow) has also been a problem. Using high-frequency tuned waveguides (400 to 500 kHz), the signal to noise ratio has been improved--but only for coolant temperatures in excess of 300°F. At full cold flow (150°F) even the tuned waveguides have been ineffective at reducing noise interference.

The feasibility of continuous AE monitoring to detect flaws in reactor pressure boundaries has been demonstrated. The Watts Bar Monitoring tests could present a significant pay-off for TVA: several of their Framatome vessels have tended to show underclad cracking. If the AE tests are acceptable, they could minimize the need for other NDT. Work is continuing on refining the AE monitoring technique (especially in the area of pattern recognition) and on generating needed standards and codes.

Because of its continuous monitoring capability, wide industrial applicability of this technique is expected in flaw detection in boilers and other pressure vessels, and in piping systems. Some specific applications could include the following:

- surveillance of highway bridge structures for detection of crack growth in welds
- integrity monitoring of composites in a variety of structures
- monitoring structural integrity of aircraft during flight
- detection and evaluation of crack growth in chemical processing systems.

REFERENCES

- Hutton, P. H. 1985. "Aircraft Structure Surveillance In-Flight Using Acoustic Emission." Second International Conference on Acoustic Emission, Stateline, Nevada.
- Hutton, P. H., and R. J. Kurtz. 1985. "Current Capabilities for Continuous AE Monitoring to Detect Flaws in Reactor Pressure Boundaries." Paper presented at the 1985 ASME Piping and Pressure Vessel Conference, New Orleans, Louisiana, June 1985. PNL-SA-13035, Pacific Northwest Laboratory, Richland, Washington.
- Hutton, P. H., et al. 1985. "Develop In-Flight Acoustic Emission Monitoring of Aircraft to Detect Fatigue Crack Growth." Final Report, Naval Air Development Center, Warminster, Pennsylvania.
- Hutton, P. H., and J. R. Skorpik. 1981. "In-Flight Fatigue Crack Monitoring Using Acoustic Emission." ISA Transactions 20(1):79-83.
- "Continuous Integrity Surveillance Using Acoustic Emission." PNL Research Results Information Sheet NDT-0610, n.d.
- "Sensors: A Growing Number of Applications." 1985. Battelle Today No. 45, November 1985.

3.1.2 ACOUSTIC EMISSION IN METALLURGY

Laboratory: National Bureau of Standards (NBS)

Contact: Roger B. Clough
Center for Materials Science
(301) 921-2965

R. B. Clough of NBS works with a group concerned with nondestructive methods of metals characterization. Recent work has focused on the measurement of AE signals in rapid solidification processing (RSP), in phase transformations, and for the vector calibration of AE transducers (Clough et al. 1984).

AE technology can be used to monitor rapid solidification, to detect flaw production during metals processing, and to provide fundamental knowledge of RSP phenomena. Another area of application of AE technology to RSP is that of laser drilling. Laser drilling is a rapidly growing manufacturing method because of its speed, controllability and capability of penetrating tough or exceptionally hard materials. However, beam power spikes and intervening disintegration products can disrupt or diminish energy transmission at the hole site, resulting in variable hole depth (Clough et al. 1984).

To improve this situation, R. B. Clough's group, under the direction of H. Wadley, has developed a new method for in situ AE monitoring of the specimen during drilling. The energy spectrum of the acoustic signal is measured and the measurement is quantified by a new procedure called "scaler calibration." The system is calibrated with a stress wave source of known energy (a pulsed infrared laser). It was found that AE energy varies as the square of the laser pulse energy. The energy of the unknown event is determined by comparison with this curve.

By monitoring the AE energy as opposed to the laser pulse energy, researchers were able to improve the statistical residuals (a measure of scatter in the depth of laser drilled holes) by about 9% (Clough et al. 1984). When combined with additional information, AE energy monitoring significantly improved the accuracy in laser hole depth determinations. This work was carried out in conjunction with R. J. Schaefer [(301) 921-2985]. Researchers feel that the method is feasible for industrial application.

AE energy measurements have been made during surface heating and cooling (melting and solidification) in various metals and alloys. Results indicate that plastic deformation and/or microfracture of the substrate controls the AE signal in both the solid and the solid/liquid regions. AE depends in a systematic way on the metallurgical condition of the substrate. The amount of AE generated during resolidification of an Al-4.5% Cu alloy and the amount of cracking are related and depend on the prior heat treatment of the substrate material. This introduces the possibility of improving the quality of surface modified layers through selective prior thermomechanical processing of the substrate and the control of defect populations by passive AE monitoring.

REFERENCES

Clough, R. B., et al. 1984. "Acoustic Emission in Metallurgy." NBS Technical Activities 1984, pp. 78-85.

3.1.3 ACOUSTIC EMISSION SOURCE LOCATION SYSTEM

Laboratory: National Bureau of Standards (NBS)

Contact: Nelson N. Hsu
Center for Manufacturing Engineering
(301) 921-3646

AE is well suited to flaw detection and location because it is highly sensitive to changes in material properties and to structural flaws not easily detected otherwise (Hsu and Fick 1984). It is a real-time, whole-field, passive monitoring technique, which can determine the location of an active flaw in a structure under load. In addition, AE only requires a few sensors attached to the structure to monitor a relatively large area (Barsky and Hsu 1985).

Commercially available AE source location systems are quite expensive, due to their need for computer-based control. In an effort to maximize the effectiveness of AE source location techniques, and to minimize system costs, N. N. Hsu of NBS has successfully developed a simple and effective AE source location system. This system requires no computer support, is totally self-contained, and can be built with inexpensive, readily available integrated circuits (Barsky and Hsu 1985).

After a detailed error analysis of AE source location techniques, findings indicated that the conventionally used planar triangulation algorithms were often subject to large errors. These errors affected the precision of the source location (i.e., flaw location) determination; however, for many applications rapid display of the approximate source location was of most importance (Barsky and Hsu 1985). Therefore, Hsu designed a system with a simplified algorithm that provides an almost instantaneous source location determination.

The system consists of three major parts: 1) four AE sensors to be attached in a square array on the surface of the structure being tested; 2) an instrumentation control module that contains all the electronic circuits; and 3) a ribbon cable that connects the module to a display unit--a 16 x 16 array of light-emitting diodes (LEDs) mapping the 16 x 16 grid of the square region (Barsky and Hsu 1985).

AE sources (flaws) are indicated on the display as lighted LEDs. The relative intensity of the LED corresponds to the number of AE events that have occurred in a particular grid region (Barsky and Hsu 1985). A schematic diagram of the system is given in Figure 3.2. Due to its low cost, ease of operation, and portability, this system should be ideal for flaw detection applications in the field.

AE techniques may also be useful for manufacturing process control and materials characterization. The feasibility of applying AE to these areas is currently being studied in the Mechanical Production Metrology Division. Preliminary work has begun on time-scaling AE signals into the audio frequency range so that human hearing can be used for signal detection (Hsu and Fick 1984).

REFERENCES

- Hsu, N. N., and S. E. Fick. 1984. "Acoustic Emission Signal Processing for Automated Manufacturing." NBS Technical Activities 1984, p. 86.
- Barsky, M., and N. N. Hsu. 1985. "A Simple and Effective Acoustic Emission Source Location System," Materials Evaluation, Vol. 43, No. 1, pp. 108-110.

FIGURE 3.2. Schematic Diagram of AE Source Location Module (Barsky and Hsu 1985)

3.1.4 NONDESTRUCTIVE EVALUATION OF TOOL WEAR AND CHIP FORMATION: ON-LINE SENSOR DEVELOPMENTS

Laboratory: National Bureau of Standards (NBS)

Contact: Kenneth W. Yee or Donald S. Blomquist
Center for Manufacturing Engineering
(301) 921-3381

Automated NDE measurements will be an integral part of the automated "factory of the future" (Yolken and Mordfin 1984). Automated machining of precision parts will require on-line sensors capable of predicting tool wear and managing chip formation. If a drilling tool fails and there is no operator to stop the machining center, the part or the machining center itself can be damaged. Long, continuous chips can entangle a robot that is loading and unloading a machining center and either stop the machining processor or damage the robot (Yee and Blomquist 1984).

K. W. Yee and D. S. Blomquist of the Automated Production Technology Division in the NBS Center for Manufacturing Engineering have developed an instrument called Drill-Up, which is designed to prevent breakage of small-diameter drills used on automatic-feed drilling machines. They have just finished assessing the potential of Drill-Up for tool-wear detection. In addition, they have investigated the feasibility of using sensors to study chip formation in single-point turning operations.

Drill-Up uses a piezoelectric accelerometer mechanically coupled to the workpiece as an input sensor. Potential breakage is determined by a time-domain analysis of the accelerometer signal. A single-chip microcomputer implements a calibration routine that automatically adjusts to the signal amplitude generated by normal drilling operations. When improper drilling occurs, a large amplitude signal that is synchronous with the drill rotation is detected (Yee and Blomquist 1984).

In many applications, however, breakage is not a normal failure mode; therefore, the determination of wear-out, or end-of-life, of the drill is of interest. Parameters in Drill-Up were subsequently altered; holes drilled with

new and worn-out drills were evaluated with the new modifications. Tests were made using 1/4, 3/8, and 1/2 inch (diameter) drills in AISI 1015 steel.

Results indicated that sharp new drills drilled larger-diameter holes at the beginning of life than during the remaining useful life; however, the diameter of the holes at the end-of-life were not significantly different from those drilled during the main part of the drill's useful life. Researchers conclude that hole size may not be a good indicator of wear-out. A study is under way of different steels and a wider range of drill diameters.

To predict chip formation, an AE Event Counter was constructed. AE signal bursts that exceed a selected threshold voltage during a given time interval are monitored with this experimental instrument.

Tests were performed on a turning center with coated carbide tooling and a chip breaker. The machined material was a 6061-T651 aluminum rod. An AE transducer was mounted at the rear of the tool holder, and the AE signal analyzed with the Event Counter (Yee and Blomquist 1984).

A detectable signal shift occurred when the cutting changed from a continuous mode (normal cutting) to a discontinuous mode (chip production); thus one could clearly predict the formation of chips from this signal transition. Further investigations will include the development of computational algorithms for chip management.

REFERENCES

Yolken, T., and L. Mordfin, "Strategic Plan for Nondestructive Evaluation," Office of NDE, NBS, December 1984, p. 17.

Yee, K. W., and D. S. Blomquist. "Nondestructive Evaluation of Tool Wear and Chip Management NBS Technical Activities 1984, pp. 87-89.

3.2 EDDY CURRENT (EC) METHODS

3.2.1 ADVANCED EDDY CURRENT COIL EXCITATION AND SIGNAL PROCESSING

Laboratory: Air Force Wright Aeronautical Laboratories (AFWAL)

Contact: James A. Holloway
AFWAL/MLLP
(513) 255-5309

Turbine engine component life-management technology now being developed under a "retirement-for-cause" (RFC) approach requires a reliable method for detecting and characterizing defects. The present high-resolution techniques for defect detection applicable to rotating components such as discs and spacers involve primarily single-frequency EC examination. As evidenced by component performance, procedures based on these techniques have effectively screened out components having life-limiting defects. However, these simple defect detection approaches will not satisfy the more stringent needs of RFC programs. New methods that provide accurate sizing of defects must be developed.

Pulsed eddy current (PEC) examination has been suggested as a possible approach to satisfy RFC program needs. PEC inspection consists of generating a pulse of current in an excitation coil, and then noting the characteristics of the signal in a receiver resulting from EC excited in the examination material. This is a contrast to conventional EC examination, in which the excitation is a continuous wave of one or more discrete frequencies. Another difference is that with conventional EC examination, the change in impedance of a single (excitation) coil is the measured parameter.

The Southwest Research Institute (SRI) undertook a project for AFWAL to develop and evaluate a PEC flaw detection capability that would be an improved means of evaluating surface and near-surface defects in low-conductivity materials used in gas turbine engine components. The specific objective was to optimize a breadboard PEC system including the probes, instrumentation, and signal analysis techniques. A specific goal was the reliable detection of 0.010-inch (0.25-mm) long by 0.005-inch (0.125-mm) wide by 0.005-inch (0.125 mm) deep surface-breaking flaws that are of interest for RFC purposes. An ultimate goal is the reliable detection and sizing of flaws of this size and

larger, for both surface-breaking and subsurface flaws, and the discrimination of such defects from various geometric configurations such as edges and corners.

The principle tasks of the SRI research were 1) analytical modeling and probe optimization, 2) assembly of an experimental pulsed EC breadboard system, and 3) comparison of the pulsed breadboard system with the state-of-the-art continuous-wave EC systems.

The breadboard PEC system successfully detected the target-size flaws. Initial results of the theory correctly predicted the field distribution from sample probes, in the absence of a flaw. Therefore, emphasis was placed on the possibility of using unique features of PEC to investigate flaw characterization. The simple theoretical models, obtained by integrating point flaw model fields over the depth of target-sized defects, could not quantitatively predict the dependence of received pulse on flaw size. Investigations determined that the probable cause of the discrepancy is that the integrated point flaw model ignores the Kahn effect--the tendency of EC to be concentrated at the tip and to be depleted at the surface of a surface-breaking flaw. This effect, if properly detected and used, could provide information about flaw depth; the time that it would take the signal from the tip-concentrated EC to appear at the surface would be characteristic of the depth of the source of concentration. This effect was modeled by the use of subsurface point flaws. Experiments confirmed the correlation with depth. To enhance this type of measurement, a new breadboard system was constructed. The new system included a unique pulser that allowed precise control of the excitation during the detection period of the pulse cycle. This enhanced the signal-to-noise ratio of the depth information. The existence of this flaw depth information in agreement with the crack tip model was confirmed.

The concept of the depth measurement technique is relatively unexplored; therefore, additional research is recommended in this area. First, the breadboard pulsing unit containing the voltage-to-current amplifier needs to deliver larger currents than is now possible at equal or better bandwidth. This would

allow a comparison between the flaw detection capability of the ramp pulse system and the more conventional bipolar pulse system that was set up at the beginning of the project.

Second, theory development should be pursued, in the area of flaw response. The models that were developed predicted successfully the spatial and temporal variation of transmitted magnetic fields due to shielded EC probes, but the integrated point flaw model is clearly inadequate to describe flaw signal behavior when flaw characterization is the goal. Although the EC paths of interest are three-dimensional in nature, researchers believe that an appropriate step is to develop an analytical two-dimensional model that could simulate a long crack with a finite depth. This is the simplest model that would self-consistently include the Kahn effect. Theory development in this area may guide probe development for depth measurement, including the use of differential receiver coils.

Third, the depth measurement approach needs to be tested on naturally occurring flaws. In theory, this measurement depends on the flaw geometry, and not only the flaw surface area, as appears to be the case with electric current perturbation and, to a lesser extent, conventional EC examination.

REFERENCES

Fisher, J. L., R. E. Beissner and J. E. Doherty. 1985. "Exploratory Development on Advanced Eddy Current Excitation and Signal Processing," AFWAL-TR-85-4025.

3.2.2 EDDY CURRENT EXAMINATION OF STEAM GENERATOR TUBES/ SURRY STEAM GENERATOR FACILITY

Laboratory: Pacific Northwest Laboratory (PNL)

Contact: R. J. Kurtz
Nondestructive Testing Section
(509) 375-2495

A unique study of NDE reliability is under way at PNL under NRC sponsorship. Project participants include the Electric Power Research Institute (EPRI) and consortia from France, Italy, and Japan. The Steam Generator Group Project (SGGP) was initiated in 1982 to conduct research leading to the validation of current and developmental NDE techniques (Birks et al. 1985). The program uses the retired-from-service Surry steam generator. A major objective of this work is to develop data on the reliability of detection and the accuracy of defect sizing provided by EC in-service inspections (Clark, Doctor and Ferris 1985).

Pressurized water reactor steam generators have suffered from a series of problems that have affected plant reliability and have raised safety concerns. In water-cooled nuclear reactors, over one-half the primary coolant for the reactor core is contained in the steam generators. The integrity of steam generator tubes must therefore be maintained in order to prevent the spread of radioactivity and to ensure adequate core cooling.

Steam generators are nondestructively inspected periodically using EC testing. An EC probe is inserted into the individual tubes of the generator. As the probe is drawn through the tubes, the EC responses are recorded. Variations in material conductivity caused by cracks, voids, metallurgical changes, or thickness changes will alter the path of the EC. Interpretation of EC data thus provides a description of cracks, wastage, and other degradation in the tubes.

Before the SGGP, very little research had been done on actual service-produced defects in steam generators, and NDT reliability in such applications had not been validated. A service-degraded U-tube steam generator was acquired

for the project and is housed in an examination facility at the Hanford Site, Washington, where it serves as a test bed (Birks et al. 1985).

During 1984 and 1985, a five-team data acquisition and analysis round robin (DAARR) was conducted using commercially available multifrequency EC equipment and ASME procedures. Each team acquired data with the multifrequency Zetec MIZ-12 EC system and bobbin coil; data was analyzed with a DDA-4 analyzer. The DAARR concluded that the teams averaged about a 75% rate of common defect detection, when all of the generator is considered. Almost all teams seemed to acquire the same EC signals at similar locations; however, significant differences were found among the teams in defect sizing. Another DAARR conclusion was that the analysts did not appear to use all of the EC data available to them through the multifrequency system. Many of the analyses relied only on the 400 kHz differential data even though other frequency and frequency mix information was available (Clark, Doctor and Ferris 1985).

The SGGP will complete experimental work during 1986. Identified defect and nondefect sections of the generator will be removed for EC examination. Selected specimens will be metallographically sectioned for NOE validation; other specimens will be burst tested to assess the validity of previously derived tube integrity models that relate burst pressure to defect type and severity (Clark, Doctor and Ferris 1985). The ultimate goal of this program is to contribute to the development of a model for steam generator in-service inspection sampling plans and to improve regulatory guidelines for tube plugging (Birks et al. 1985).

REFERENCES

- Birks, A. S., et al. 1985. "Reliability of Eddy Current Examination of Steam Generator Tubes." 11th World Conf. NDT, Las Vegas, Nevada, November 1985.
- Clark, R. A., P. G. Doctor and R.H. Ferris, "Surry Steam Generator - Examination and Evaluation," Presented at the Light Water Reactor Meeting, Washington, D.C., Oct. 1985.
- "Solving Materials Reliability Problems," Battelle Today, No. 30, Nov. 1982.
- Birks, A. S., et al., "Preliminary Report on Steam Generator Group Project - Task 9: NDE Round Robin," Report to the U.S. Nuclear Regulatory Commission, Nov. 1984.

Heasler, et al. "Performance Demonstration Tests for IGSCC Detection," Report to the U.S. Nuclear Regulatory Commission, Nov. 1985.

3.2.3 EDDY CURRENT INSTRUMENTATION DEVELOPMENT

Laboratory: Pacific Northwest Laboratory (PNL)

Contact: James M. Prince
Nondestructive Testing Section
(509) 375-2469

PNL is involved in EC probe and signal-processing instrumentation R&D. The work emphasizes the application of EC NDT methods and signal-processing techniques to specific inspection requirements (Prince, Reid and Lessor 1985). Instruments developed over the past few years have included an automated EC cartridge case inspection module; a sweep frequency EC instrument capable of 12,288-step operation over the 10 kHz to 10 MHz frequency range; and a new two-frequency EC instrument (Prince, Reid and Lessor 1985). Special probes that have been developed include a ferromagnetic resonance (FMR) probe for incorporation in an advanced surface flaw detection system.

The EC inspection module can detect cracks and subsurface defects in brass cartridge cases. The automated system inspects (and rejects bad parts) at the production rate of twenty cartridge cases per second. In addition to detecting flaws, the EC instrument can measure case hardness to verify heat treatment. This system, and other digital control and signal-processing techniques developed by PNL, represent significant advances in the automation of EC NDT for industrial applications.

The sweep frequency EC instrument is an advanced, digitally controlled, wide-range multifrequency instrument. It is computer-controllable to permit complex test sequences at many frequencies using a single probe. The computer interface also provides for remote operation of the instrument; it can be applied to any test situation where a direct operator/instrument interface is not wanted. Recently, the instrument has been used in an EC data acquisition system providing surface oxidation depth profiles on PGX graphite--material used in high-temperature, gas-cooled nuclear reactors.

The two-frequency EC instrument was developed to measure Zircaloy clad thickness on slightly enriched uranium fuel elements for UNC Nuclear Industries (Richland, Washington). As part of the company's quality assurance program,

UNC Nuclear required fuel elements to be 100% surface inspected for Zircaloy clad thickness. The conventional inspection method used a single frequency EC instrument and a surface riding probe. However, this instrument required extensive manual setup and calibration. Failure rates of the probes were very high, due to the rough nature of the fuel element surface. The EC instrument developed by PNL simplifies the operator interface and increases inspection reliability and throughput (Prince, Reid and Lessor 1985).

Operated at 50 kHz and 5 MHz simultaneously, the two-frequency EC instrument amplitude-detects each signal to provide thickness/liftoff and liftoff data respectively. The data are then mathematically processed in real time to provide a clad thickness value independent of liftoff. Automatic calibration and polynomial coefficient generation algorithms are used in the instrument.

A project is under way to adapt the two-frequency EC instrument to the inspection of metal detonator cords. Initially, rounds of about 0.1 inch diameter will be inspected. A chevron-shape with 0.010 inch nominal wall thickness will eventually be inspected. The job requires fabrication of special EC probes and instrumentation. The circuitry being developed could be readily adapted to other EC inspections.

The FMR probe developed at PNL is an advanced rotary EC probe based on the YIG (Yttrium-Iron-Garnet) ferromagnetic resonance phenomena. The rotary probe consists of an active FMR probe operating at 850 MHz, and a signal processor that converts the operating frequency and amplitude output to dc voltage levels; these are then transferred through slip rings for analysis. Key features of this probe include its small EC field diameter (0.015 inches) and its relatively low sensitivity of liftoff variations. These features allow the probe to reliably detect and size cracks in tight complex geometries.

This work has made extensive use of EC theoretical analyses developed by Caius V. Dodd of ORNL, for example in the initial design of several EC systems. PNL's ongoing effort to apply advanced signal-processing techniques to the automation of EC NOT inspections is evidenced in its recent development of a computer program to handle samples up to nine layers (of differing conductivity and thickness) and to determine EC test parameters such as frequency, liftoff, and sensitivity on such complex samples.

REFERENCES

- Prince, J. M., L. D. Reid and D. L. Lessor, "Two-Frequency Eddy Current Instrument for Measuring the Thickness of Zircaloy Cladding on Uranium Conditions of Varying Lift-Off," Materials Evaluation, 43, No. 12, 1562-1565, Nov. 1985.
- "Automated Eddy Current Cartridge Case Inspection Module." PNL Research Results Information Sheet EC-D01, n.d.
- "Sweep Frequency Eddy Current Instrument," PNL Research Results Information Sheet EC-002, n.d.
- "Advanced Ferromagnetic Resonance Eddy Current Probe," PNL.
- "Exploratory Development of FMR Advanced Surface Flow Detection Methods," PNL Final Report, AFWAL - TR-85-4010, April, 1985.

3.2.4 EDDY CURRENT INSPECTION RESEARCH

Laboratory: Oak Ridge National Laboratory (ORNL)

Contact: C.V. Dodd
Nondestructive Testing Group
(615) 574-4839

One of the major areas of research at ORNL is the development of EC inspection techniques and equipment. EC inspection involves observing how electromagnetic currents induced in a material are affected by the defects that the material contains. EC techniques have been used to examine seam welds in the sheath of superconductor cables, stainless steel plate welds, and steam generator tubing. Although adaptations of the technique are required for each individual application, the theory remains essentially the same for each process.

A major problem encountered in the inspection process, particularly with sheathing or generator tubing, involves the separation of signals generated by the properties of interest from extraneous signals. Extraneous signals can be caused by noncritical factors such as variations in conductivity, permeability, weld contour, coil to specimen spacing, and tube supports. Conventional EC techniques use only a single frequency and measure the amplitude and phase of the resulting signal; therefore, they are only able to separate two variables. Researchers at ORNL have developed the capability for solving multi-parameter problems through the use of multifrequency techniques. By measuring the amplitude and phase of the signal at several different frequencies and by using efficient data processing equipment, the effects of different property variations can be sorted out. Work has involved both ferromagnetic and non-ferromagnetic materials. The software used to process the signals and make the complex calculations required to interpret the data was developed using both theoretical models and experimental measurements on specimens known to contain flaws.

In addition to the multifrequency concept and the related processing software, ORNL researchers have developed mechanical systems to aid in the EC

inspection process. An automatic system for examining the weld seams on super-conductor cable sheath has been installed in an Airco plant that manufactures the cables. As the weld advances linearly through the inspection station, the system reciprocates a probe transversely across the weld seam and heat-affected zone of the sheath. The system is capable of detecting flaws as small as 0.5 mm deep (0.020 inches), and is placed just a few feet after the welding station, allowing prompt detection and adjustment of the welding parameters if necessary.

The development of more sensitive signal probes is also emphasized, particularly to enhance flaw detection in steam generator tubing. The latest probe design, incorporating an array of small, flat "pancake" coils, improves both the detection of small flaws and the rejection of tube support signals.

REFERENCES

Smith, J. H., C. V. Dodd and L. D. Chitwood, 1985. "Multifrequency Eddy-Current Examination of Seam Weld in Steel Sheath," Materials Evaluation, 43(12):1566-1572.

3.2.5 EDDY CURRENT JET ENGINE DISK-CRACK MONITOR

Laboratory: NASA Lewis Research Center (LeRC)

Contact: John P. Barranger
(216) 433-6019

Rotating parts present the most critical design and maintenance problems in an aircraft turbine engine. Modes of failure depend on the material and on the operating environment (stresses, vibration, and temperatures). Maintenance reports from compressor, fan, and turbine disk inspections indicate that cracks frequently propagate from the blade root area of the disk rim. An EC disk-crack monitor developed at LeRC is designed to detect these cracks while the turbine is in operation.

Until recently, disks were retired based on a limited-life calculation that predicted the lifetime of the average disk. A disk that had been in operation for its predicted lifetime was removed whether or not it had useful life remaining. A new method of parts replacement, called retirement-for-cause (RFC) optimizes service life by considering each part individually. RFC relies on parts inspection, fracture mechanics analysis and the predictability of crack propagation.

The successful application of RFC depends on accurate and reliable inspection techniques. Installing a sensor in the engine has the advantage that monitoring is possible, before, during or after a flight, eliminating the need for engine disassembly for inspection. Engine-mounted sensors must operate in a severe operational environment; therefore, the technology to develop an accurate, reliable and rugged sensor is needed before the full potential of RFC on-engine inspection can be realized.

The sensor developed by LeRC consists of palladium-silver alloy wire wound around an alumina bobbin (Figure 3.3). The wire is covered by a ceramic insulation that is left in an uncured state during manufacturing, which provides mechanical flexibility for handling and winding. After winding on the bobbin, the insulation is cured to its final ceramic, rigid state. Tests that

FIGURE 3.3. Simplified Block Diagram of Crack Monitoring Sensor (Barranger 1984)

subjected the wire to temperatures of 650°C (1200°F) for 1000 hours with only slight deterioration in properties demonstrated the durability of the finished product.

The sensor is designed to measure conductance changes in a circuit; when the circuit is compressed by a turbine disk the conductance change can be inferred to result from a crack in the disk. The sensor is placed so that the face of the bobbin is approximately 3 mm from the disk rim. The sensor lead wires are routed up through the core of the vane exiting to the outside of the engine through a pressure-tight fitting. Shielded engine cables carry the sensor signals to an automatic capacitance-conductance bridge. There are two phase detectors in the bridge, one whose output voltage is proportional to unbalanced capacitance and another whose output voltage is proportional to unbalanced conductance. The latter is used for crack detection because it was found to be less sensitive to variations in the spacing between the sensor and

the disk rim. As the blade root region passes the sensor during the monitoring time, the conductance phase detector senses changes in inductance of the sensor coil. The detector signal is digitized and averaged before being displayed on an oscilloscope.

The sensor was engine tested at ground idle speed and temperature. The system was able to detect a 3.5-mm-long radial crack under these conditions. Although further evaluation is necessary to prove the long-term reliability and inspection suitability of the sensor, the preliminary tests indicate that an engine-mounted detector has potential for RFC inspections.

REFERENCES

- Barranger, J. P. 1984. "Eddy Current Jet Engine Disk-Crack Monitor." Materials Evaluation, Vol. II, pp. 1374-1378, October 1984.

3.2.6 EDDY CURRENT PROBE DEVELOPMENT

Laboratory: Air Force Wright Aeronautical Laboratories (AFWAL)

Contact: Dale Chimenti
Project Engineer
(513) 255-5309

Without an inexpensive and accurate method of determining the suitability for further service of turbine disks in gas turbine engines, it is necessary to retire these expensive aircraft components after a predetermined operational life because they may contain cracks that approach critical size. This operational life is based on the worst-case fatigue performance exhibited when disks are tested to destruction using simulated operational duty cycles. Because component lives may vary by an order of magnitude or more under nominally identical conditions, many of today's components are being retired after a small fraction of their potential useful life. Savings would be substantial if NDE techniques could be developed to distinguish those components capable of additional duty from those that should be retired for cause.

SRI International undertook a project for AFWAL to develop two novel EC probes fabricated using printed-circuit techniques. One of the probes developed is a quarter-wave microstrip resonator that operates at 1 GHz. The second uses a broadband printed-circuit coil that can be operated in a frequency range of 10 to 400 MHz.

EC inspection has been used widely for more than 30 years, but improvement is needed in sensitivity, resolution and reproducibility. An improved analytical understanding is also needed to optimize probe design and to identify the key parameters required for setting realistic specifications.

Commercial EC probes are generally wound-coil and operate at 100 kHz. Tests were conducted using the two novel probes, commercially available wound-coil probes and a modified floppy-disk tape head. The probes were evaluated using both open and closed surface-connected flaws in metal samples. Data was collected on crack-detection sensitivity, resolution, liftoff discrimination and reproducibility.

The results are summarized as follows:

- The microwave (1-GHz) probe achieved the greatest sensitivity to open slots. However, it was also very sensitive to liftoff and stringent mechanical tolerances had to be maintained during fabrication to achieve reproducibility.
- The floppy-disk (100-kHz) probe achieved the greatest sensitivity to closed cracks. However, it was not very sensitive to the small EDM slot in the titanium annulus, possibly because of difficulties in making the probe surface conform to the curved surface of the hole.
- The printed coil (125-MHz) probe operated at a frequency intermediate to the frequencies used for microwave and floppy-disk probes, and exhibited intermediate levels of defect sensitivity, as well as an intermediate sensitivity to liftoff.

In general, these results suggest that high frequencies should be used to detect open cracks and that lower frequencies should be used to detect closed cracks. However, the observed difference in crack sensitivity could also be caused in part by differences in probe material and geometry.

The microwave probe developed during this program seems well suited for detecting small open flaws in parts that can be mechanically scanned past a fixed probe. The printed-coil intermediate-frequency probe offers good sensitivity to both open and closed flaws, good reproducibility, and moderate maneuverability. Therefore, when properly applied, both of these probes should provide an improved capability in EC testing.

REFERENCES

- Bahr, A. J., and J. P. Watjen. 1981. "Novel Eddy-Current Probe Development." AFWAL-TR-81-4159, December 1981.

3.2.7 EDDY CURRENT SENSORS FOR SMALL FLAW DETECTION IN METALLIC COMPONENTS

Laboratory: Air Force Wright Aeronautical Laboratory (AFWAL)

Contact: Dale Chimenti
Project Engineer
(513) 255-5309

The goal of the Retirement-for-Cause (RFC) maintenance program conducted by the United States Air Force is to extend the life of gas turbine engine components beyond their predetermined "safe life" limit through the use of NDE techniques. The development of reliable NDE equipment is crucial to the success of the program. Under the direction of AFWAL, researchers at PNL have developed a reproducible, high-sensitivity microwave EC probe for the detection of surface cracks in metallic components. The simplicity and small size of the probe make it ideal for regions where access is limited, such as a bolt hole.

The techniques studied in this research were based on the microwave ferromagnetic resonance (FMR) EC probe that had been under development at Stanford University for several years prior to the work at AFWAL. Stanford researchers had demonstrated the ability of the technique to detect extremely small surface cracks. The goal of the project was to advance and implement the FMR to

- 1) provide a high degree of sensitivity to extremely small surface cracks,
- 2) discriminate against spurious signal sources, and 3) provide a practical and reproducible probe design for possible use in the RFC program.

Two techniques for implementing the FMR probe were studied and evaluated. The first technique used the FMR probe as a passive device; data was collected by observing the reflection coefficient of the probe driven from a 50 ohm microwave system. In the second technique, the probe operated as the resonator in a microwave oscillator, forming an active probe, and yielding data on the frequency of the probe circuit oscillation. Both techniques required the fabrication of signal processors designed to evaluate the theoretical analysis as it applied to optimizing the signal-to-noise ratio of each technique, where the signal is considered to be caused by both flaws and noise.

Experimental work with the passive probe was terminated in favor of developing the active probe, which researchers concluded offered a much more practical approach. This was based on the passive probe's overwhelming drawback as a field instrument, specifically its inability to provide flaw detection when driven outside of an extremely narrow band of frequencies that must correspond to the FMR probe's resonance. The practical aspect of this characteristic arises in the requirement placed on the microwave-driving electronics; the output frequency must be matched with the FMR probe resonance and held there against all effects tending to change it, except surface flaws. The active probe, which utilizes the FMR probe as the resonator in a microwave oscillator, circumvents this drawback because the active probe self-generates its own drive frequency directly at the FMR probe's resonance.

The AFWAL research with several probes using the positive elements of the experimental studies shows the excellent potential of the microwave EC probe for NDE examination, especially where extremely small surface-connected flaws must be detected in locations of restricted geometries.

REFERENCES

- Prince, J. M., and B. A. Auld. 1982. "Research to Develop and Evaluate Advanced Eddy Current Sensors for Detecting Small Flaws in Metallic Aerospace Components." AFWAL-TR-82-4155, Battelle, Pacific Northwest Laboratory, Richland, Washington, December 1982.

3.2.8 FMR ADVANCED SURFACE FLAW DETECTION METHODS

Laboratory: Air Force Wright Aeronautical Laboratories (AFWAL)

Contact: Joseph Moyzis
AFWAL/MLLP
(513) 255-5309

PNL undertook the development of a breadboard surface flaw detection system for the detection of fatigue cracks in complex geometry engine components made of Ti 6-2-4-6 or IN-100. This system uses a microwave EC (MEC) probe operating on the FMR principle. Using a Gallium-doped Yttrium Iron Garnet (GaYIG) sphere coupled to an excitation current source, and placing the sphere close enough to a conductive material so that the processing field links with the material, EC are induced into the material. The PNL approach utilized the FMR probe in an active mode in which it operated as the resonant element of a microwave oscillator circuit at frequencies ranging from 600 to 1,100 MHz. Theoretical and experimental work characterized the FMR-MEC probe's surface flaw detection sensitivity as a function of probe liftoff, specimen material, specimen geometries in the area of the flaw and flaw length, depth and closure. A breadboard MEC flaw detection system was then designed and assembled to inspect the key slot geometry on a jet engine interstage seal component to assess the potential for inclusion into the RFC modular inspection system. A demonstration verified the breadboard system's practical performance and capabilities.

Based on laboratory experiments and theoretical studies, a rotary probe inspection system was developed for inspecting small-radius curved surfaces as well as flat surface geometries. The experimental results achieved with the rotary probe demonstrate that the extremely high operating frequency of the active FMR EC probe does not limit its effectiveness for crack detection in conditions of widely varying liftoff. This system also demonstrated that the active FMR probe and signal processor circuitry can be made practical, simple, and compact. One of the primary advantages of the active FMR probe over conventional coil probes is its extremely small effective EC field diameter (or crack detection resolution)--0.38 mm utilizing a 0.30 mm YIG. This is important for sizing cracks in tight geometries. With hybrid integrated

circuit fabrication techniques, it should be possible to reduce the diameter of the small-radius active FMR probe to inspect even tighter geometries, such as 3.13 mm diameter cooling holes with an effective EC field resolution of less than 0.38 mm.

REFERENCE

- Prince, J. M., and B. A. Auld. 1985. "Exploratory Development of FMR Advanced Surface Flaw Detection Methods." AFWAL-TR-85-4010, Battelle, Pacific Northwest Laboratory, Richland, Washington, April 1985.

Laboratory, National Bureau of Standards (NBS)

Contact: Frederick J. Hopark
Center for Materials Science
(301) 975-3851

The use of polymers in structural applications has grown considerably during the past decade (Hopark 1984). One of the biggest problems in the new field of polymer processing, however, is the lack of basic knowledge of process control in polymer systems. This lack of knowledge is the major block in the automation of polymer processing.

3.3 ELECTRICAL METHODS

Frederick J. Hopark of the Polymers Division in NBS's Center for Materials Science has developed a new method of polymer cure monitoring that relies on the use of on-line process control. The NBS Time Domain Dielectric Spectrometer measures dielectric loss in a curing polymer to obtain information on structural modification. A big advantage of this technique over the more conventional frequency probe is that the time domain method can measure a wide range of frequencies in a very short time. With the NBS spectrometer, data in the frequency range of 10^0 to 10^6 Hz can be measured. For a minimum frequency of 10^0 Hz, a signal can be acquired in 300 s with a total measurement and digitalization time of 15 min. (Hopark 1984a).

A block diagram of the dielectric spectrometer is given in Figure 3.4. The major components include a step generator, a charge amplifier (the input for an amplifier/differentiator), an analog-to-digital converter, a computer, and a 16-bit microcomputer.

In general, the measurement proceeds as follows: 1) electrodes are attached to a sample of resin; 2) the sample is subjected to a step input of voltage; 3) a transient current is set up in the resin and its change over time is monitored by the detector; and 4) the signals are digitized and mathematically transformed into a graph of dielectric loss as a function of frequency.

The key to the whole apparatus is the control clock, a time-running 10-MHz crystal oscillator, previous attempts at time-domain measurement used logarithmic clocks (Hopark 1984b). The clock used here can output any

3.3.1 CURE MONITORING IN POLYMERS VIA DIELECTRIC SPECTROSCOPY

Laboratory: National Bureau of Standards (NBS)

Contact: Frederick I. Mopsik
Center for Materials Science
(301) 921-3851

The use of polymers in structural applications has grown considerably during the past decade (Mopsik 1984a). One of the biggest problems in the new field of polymer processing, however, is the lack of basic knowledge of process control in polymer systems. This has been a stumbling block in the automation of polymer processing.

Frederick I. Mopsik of the Polymers Division in NBS's Center for Materials Science has developed a new method of polymer cure monitoring that holds promise for on-line process control. The NBS Time Domain Dielectric Spectrometer measures dielectric loss in a curing polymer to obtain information on molecular mobilities. A big advantage of this technique over the more conventional audio frequency bridge is that the time domain method can measure a wide range of frequencies in a very short time. With the NBS Spectrometer, data in the frequency range of 10^4 to 10^{-4} Hz can be measured. For a minimum frequency of 10^{-3} Hz, a signal can be acquired in 300 s with a total measurement and computational time of 12 min. (Mopsik 1984a).

A block diagram of the dielectric spectrometer is given in Figure 3.4. The major components include a step generator, a charge amplifier (the detector), an amplifier/filter chassis, an analog-to-digital converter, a control clock, and a 16-bit minicomputer.

In general, the measurement proceeds as follows: 1) electrodes are attached to a sample of resin; 2) the sample is subjected to a step application of voltage; 3) a transient current is set up in the resin and its change over time is monitored by the detector; and 4) the signals are digitized and numerically transformed into a graph of dielectric loss as a function of frequency.

The key to the whole apparatus is the control clock, a free-running 10-MHz crystal oscillator; previous attempts at time-domain measurement used logarithmic clocks (Mopsik 1984b). The clock used here can output any rate

FIGURE 3.4. Block Diagram of NBS Time Domain Dielectric Spectrometer (Mopsik 1984b)

from 1 μ s to 10 s with the first two decades in a 1,2,5 sequence. It can also be switched to a new rate while the measurement is in progress, and still be synchronous with the original trigger event.

In practice the variable-rate clock takes samples initially every 5 μ s, then every 100 μ s, and finally every 10 s past 200 s, which is needed to carry out a proper data sampling for any length measurement. The rapid initial sampling is needed for information of the high frequencies, whereas the low-frequency information is at long times where all the high-frequency information has decayed away and the signal changes slowly.

Thus, the spectrometer permits rapid measurements during the early, fast portions of the cure and longer measurements extending to lower frequencies toward the end of the cycle, when polymerization changes are less rapid. Proper monitoring of this end of the cycle is critical, because incomplete cure is a major problem in composite curing.

Another unique feature of the NBS Time Domain Dielectric Spectrometer is the electrode design. Epoxy will bond to the electrodes as the cure proceeds; therefore, a measuring system has been designed that uses inexpensive electrode sets that are both highly reproducible and disposable (Mopsik 1984a).

The cures of several polymers have been followed, including some aged materials where the cure was short. Researchers believe the method could be readily applied in an industrial environment. An extra area of resin could be squeezed out of a product, or an extra coupon could be fabricated to follow the cure.

Future work will include relating mechanical properties of polymers and composites to the cure cycle. Variables studied would include time/temperature and length of extended cure. The goal is to use dielectric measurements with other measurement methods, such as mechanical characterization, to establish a firm basis for cure monitoring, with the ultimate goal of in-process control. The instrument is now being developed commercially by IMASS, Inc.

Also of interest in cure monitoring is a wide dynamic range automated constant-frequency measuring system developed specifically for this project.

The instrumentation is especially useful early in the cure when DC conductivity clearly dominates the measurements made so far.

REFERENCES

- F. I. Mopsik, "Cure Monitoring in Polymers and Composites Via Dielectric Spectroscopy," NBS Tech. Activities 43-45 (1984a).
- F. I. Mopsik, "Precision Time-Domain Dielectric Spectrometer," Rev. Sci. Instrum. 55, 79-87 (1984b).

3.3.2 MICROWAVE MEASUREMENT OF THE COMPLEX DIELECTRIC TENSOR OF ANISOTROPIC SLAB MATERIALS

Laboratory: Lawrence Livermore National Laboratory (LLNL)

Contact: Ray King
Lawrence Livermore National Laboratory
(415) 422-7045

A linear polarized electromagnetic wave incident on an anisotropic material suffers attenuation, phase change, and depolarization upon transmission through or reflection from the material. The electrical properties of a wave transmitted through dimension lumber can be used to determine the complex dielectric tensor. The theory that applies equally to other lossy and anisotropic materials, such as manmade composites having a 2×2 uniaxial tensor, is based on the measurable attenuation, phase change, and depolarization. A microwave system was developed for measuring these parameters. Extensive experiments were conducted at 4.81 GHz on Douglas Fir to measure moisture contents ranging from dry to complete saturation. The technique shows considerable promise as an accurate nondestructive diagnostic tool for evaluating the electrical, and therefore, the physical and mechanical properties of semitransparent anisotropic materials.

REFERENCES:

A Bibliography prepared by the Nondestructive Testing Information Analysis Center, September 5, 1985.

3.4 MAGNETIC METHODS

3.4.1 FERROGRAPHY OF WEAR DEBRIS PARTICLES

Laboratory: National Bureau of Standards (NBS)

Contact: A. William Ruff
Center for Materials Science
(301) 921-2966

NBS staff, under the direction of A. W. Ruff, are researching improved methods of monitoring wear in mechanical systems. The conventional method of detecting early wear in engines and kinetic mechanical assemblies is chemical analysis of the lubricating oil or system fluid. Recently, there has been interest, especially within the DOD, in examining the wear debris particles contained in the spent lubricating fluid. Changes in the density of wear debris particles relative to time have been correlated with changes in the rate of wear in engines and bearing systems (Ruff and Harris 1984).

The technique being studied is ferrography. Wear debris particles are first extracted from the lubricating fluid by a magnetic method, then passed through a variable gradient magnetic field. This field separates the particles by size as they settle onto a glass slide. The slide is viewed under an optical microscope with a densitometer attachment. The density of wear particles on the glass slide is correlated with particle size to evaluate the rate of wear.

Wear condition monitoring groups, in this country and overseas, have used this ferrographic technique; however, there has been considerable disparity in results from different laboratories. To standardize the procedure, researchers have developed a method of calibrating the densitometer using a neutral filter step density slide. They are also developing a photographic replica to serve as a reference for the densitometer measurements (Ruff and Harris 1984). Interlaboratory test comparisons are planned using NBS specimens and density standards.

REFERENCES

Ruff, A. W., and J. Harris. 1984. "Ferrographic Study of Wear Debris Particles," NBS Technical Activities 1984, p. 148.

3.4.2 INFLUENCE OF FATIGUE AND STRESS OF MAGNETIC PROPERTIES

Laboratory: Ames Laboratory (Ames)

Contact: B. B. Thompson
(515) 294-7803

Mechanical treatment, stress, chemical composition, and thermal history affect the magnetic properties of materials. Ames has initiated a research program on the effects of various influences on magnetic properties.

A commercial microprocessor-controlled hysteresisgraph has been developed. Among other functions, an anhysteretic magnetization curve can be obtained that provides additional information on the material properties.

Initially, the influence of carbon (C) content on the magnetic properties of steels was studied. The C forms iron carbide inclusions of different sizes, shapes, and density, which restrains the movement of domain walls and thus affect the hysteresis losses. Annealing significantly reduces the hysteresis and remanence. Conversely, plastic deformation increases the hysteresis and coercivity.

Systems capable of measuring the acoustic and magnetic Barkhausen effects have also been developed. These effects are caused by discrete jumps of domain walls due to pinning. Initial results obtained on polycrystalline Fe and Ni samples indicated pronounced and systematic variations of the signals as a function of grain size and plastic deformation.

In addition to continuing work on the magnetic properties of several types of steels and Ni, some simple magnetic alloys (Ni-Cu, Ni-Co alloys) are being studied to better understand the fundamental physics and metallurgy involved in these processes.

In the future, high-temperature measurements will be of major interest; certain types of steel processing, such as case hardening and tempering, may provide signals useful for in situ monitoring of the products.

3.4.3 MAGNETIC METHODS OF NONDESTRUCTIVE TESTING

Laboratory: National Bureau of Standards (NBS)

Contact: Lydon Swartzendruber
Center for Materials Science
(301) 921-2955

L. Swartzendruber, of NBS works closely with the ASTM Committee on Non-destructive Testing (E.7.). He provides technical assistance in the development of useful standards for magnetic particle inspection and other magnetic methods, such as the use of electronic detectors called Hall probes and the Barkhausen technique--a method now being used to measure residual stress in ferromagnetic material.

Magnetic particle inspection (MPI) procedures use "magnetic leakage fields" to locate defects in ferromagnetic materials. The method involves magnetization of the test material, then subsequent detection of "leakage fields" resulting from any defects present in the materials. A common technique involves spraying or flowing minute magnetic particles over the magnetized test surface. Patterns formed on the surface indicate the location of surface or subsurface defects (Oehl and Swartzendruber 1982).

A new military standard (MIL-STD-1949) on magnetic particle inspection techniques was prepared for the DOD (Army Materials and Mechanics Research Center 1985). It incorporates some of the new, science-based concepts for magnetic particle characterization developed at NBS. In addition, the rules previously used to approximate required current levels have been revised.

The critical factor in obtaining successful MPI results is the choice of a proper magnetizing level. Leakage field strengths are commonly too low to attract magnetic particles. A preferred approach is to apply a magnetic field to the point where many particles are attracted (after the first magnetization), then to reduce the magnetization for the actual inspection.

Ideally, the use of Hall probes is advised to measure tangential and perpendicular leakage field components. Experimental and theoretical studies have

demonstrated that a magnetic field of 30 to 80 gauss parallel to, and directly above, the surface of the part being tested will ensure the most satisfactory PI results (Swartzendruber 1984).

MPI is a relatively simple and inexpensive method that provides rapid and effective detection of defects in ferromagnetic materials. It may be applied to raw material, billets, finished and semifinished components, welds, and in-service parts. It is not applicable, however, to nonferromagnetic metals and alloys, such as austenitic stainless steel.

L. Swartzendruber's work has brought a solid scientific base to this very popular NDE method. He sees growing future interest in the automation of magnetic NDE using arrays of Hall probes and other electronic detectors.

REFERENCES

Army Materials and Mechanics Research Center, "Military Standard - Inspection, Magnetic Particle," MIL-STD-1949, Watertown, MA, August 1985.

Oehl, C. L., and L. J. Swartzendruber, "On the Optimum Applied Field for Magnetic Particle Inspection Using Direct Current." J. Nondestructive Evaluation, 3, No. 3, 1982, 125-134.

"Standard Practice for Magnetic Particle Examination," ASTM Standard E709-80, American Society for Testing and Materials, Philadelphia, 1985.

Swartzendruber, L. J., "Magnetic Leakage and Force fields for Artificial Defects in Magnetic Particle Test Rings," Proceedings 12th Symposium Nondestructive Evaluation, Research Institute, San Antonio, TX, April 1979, 150-162.

Swartzendruber, L. J., "Magnetic Measurements," NBS Technical Activities 1984, 139-140.

3.5 RADIOGRAPHY AND RADIATION METHODS

3.5.1 DIRECT CONVERSION X-RAY IMAGING DETECTORS

Laboratory: National Bureau of Standards (NBS)

Contact: Masao Kuriyama
Center for Materials Science
(301) 921-2986

Under the direction of M. Kuriyama, NBS researchers are working on the development and characterization of x-ray imaging detectors. Recent work has studied direct conversion detectors, such as the commercial x-ray vidicon camera and the charge coupled device (CCD) image sensor. Both detectors directly convert the charge carriers generated by x-rays striking a target into a video signal, without the intervening conversion to light (Spal, Burdette and Kuriyama 1984).

The x-ray vidicon camera, which is commercially available, had a minimum detectable intensity (for 8-keV radiation) of 10^8 photons/cm²/s, and a spatial resolution of 25 μ m.

No commercial CCD area image sensor for x-rays is available; however, several commercial devices intended for visible radiation have been studied for their x-ray response. In addition, some research CCDs have been optimized for x-rays (Spal, Burdette and Kuriyama 1984).

Researchers have tested the Texas Instrument TC201 CCD. It has an active area of 6 x 8 mm, with a pixel size of 24 μ m. A dynamic range of 1000 is obtained. Conventionally, the device is scanned at 60 Hz for a standard video signal, but with circuitry modifications researchers were able to adapt the device to image x-rays over an energy range of 5 to 100 keV. Excellent spatial resolution (2 to 10 μ m) may be achieved with this device using a smaller pixel size detector now available.

REFERENCES

Spal, R. D., H. E. Burdette and M. Kuriyama, "Direct Conversion X-ray Imaging Detectors," NBS Technical Activities 1984, 106-107, November 1984.

3.5.2 DYNAMIC RADIOGRAPHIC IMAGING USING HIGH-SPEED VIDEO

Laboratory: Los Alamos National Laboratory (LANL)

Contact: Lawrence Bryant
(505) 667-8271

High-speed video equipment can be used to optically image up to 2000 full frames per second or 12,000 partial frames per second. X-ray image intensifiers have been used to image radiographic images at 30 frames per second. By combining these two types of equipment, it is possible to perform dynamic x-ray imaging of up to 2000 full frames per second. In this technique, the high-speed video camera records the output of an x-ray image intensifier. By playing the tape back at a lower speed the equipment can be a very powerful and convenient motion analysis system. Typical applications of this dynamic imaging technique include 1) boiling type action of liquids in metal containers; 2) compressor operation with visualization of crank shaft, connecting rod and piston movement; and 3) thermal battery operation.

One possible imaging method combines optical and x-ray capabilities to observe both the external and internal details of an object or event. Two cameras are used in this method, one in a visual mode and the other in an x-ray mode, thus allowing both kinds of images to appear in a synchronized presentation.

The components that make up the high-speed video/x-ray imaging system include radiographic sources, the x-ray image intensifier and the associated optics required to interface the video camera with the image intensifier.

Sources of x-rays or gamma rays for high-speed video/dynamic radiography can be conventional NDT x-ray generators or radioactive isotopes. Although pulsed sources can be used if the frame rate of the video system is synchronized with the pulse rate of the radiation source, the simplest and most common sources are steady-state sources. Steady state is important in order to have a constant output of light from the x-ray image intensifier and to avoid varying voltages and currents and hence varying magnetic fields near the high-speed video camera cable. This condition can introduce severe electronic distortion into the video images. The constant potential x-ray generators have a

reasonably uniform output of voltage and current that minimizes light output variations and magnetic field interference. Many other industrial x-ray generators are not constant potential (self-rectified) and can be used for the high-speed video dynamic radiography; however, the varying brightness of the images and the interference patterns are quite distracting.

REFERENCES

Bryant, L. E., Jr., "Development of a Dynamic Radiographic Capability Using High-Speed Video," Los Alamos National Laboratory, 1984.

3.5.3 HIGH AVERAGE POWER INDUCTION ACCELERATOR

Laboratory: Lawrence Livermore National Laboratory (LLNL)

Contact: Daniel L. Brix
Lawrence Livermore National Laboratory
(415) 422-7045

The high average power induction accelerator generates 70-ns bursts of electrons (2000A) and gives them an energy of 2 million eV. The accelerator exceeds previously available power levels by two orders of magnitude and repetition rates by one order of magnitude. It is several times more reliable than previous units and is smaller per unit of energy imparted to the electrons.

The accelerator's capabilities were made possible by the development of the MAG I magnetic-pulse compression driver. The MAG I takes a 1- μ s pulse and uses nonlinear magnetics to compress it into a 70-ns pulse.

The accelerator was designed to generate beams for beam propagation, microwave or laser beam generation, and radiographic applications. It may also be useful as a radiation source for industrial applications such as medical device sterilization, polymer modification, waste treatment, and food preservation.

REFERENCES

Research & Development, "I.R. 100 Competition Winners," October 1985.

3.5.4 HIGH-RESOLUTION NONFILM RADIOGRAPHY

Laboratory: Air Force Wright Aeronautical Laboratories (AFWAL)

Contact: Lee R. Gulley
AFWAL/MLTM
(513) 255-3612

The Manufacturing Technology Division of the AFWAL has recently completed and demonstrated an advanced nonfilm radiographic inspection system. The system provides cost reduction over conventional x-ray methods as much as ten to one and meets or exceeds the military specification for radiographic sensitivity on thin structural materials. Previously developed nonfilm radiographic systems could not meet these standards on materials less than one inch thick. Since most military designs include extensive use of thin-gauge, high-strength, lightweight materials, it was essential to extend the measurement capability down to one tenth of an inch. The AFWAL system consists of an x-ray source, an x-ray image amplifier, a video camera, and various parts handling and image processing equipment.

Microfocus x-ray tubes are required for nonfilm radiography because of the magnification and resolution requirements of the process. The AFWAL system uses a Magnaflux MXK-100M microfocus x-ray tube that can provide a focal spot of 50 microns or less.

The x-ray image amplifier is a modification of amplifiers commonly used in medical applications. Medical amplifiers are designed with a high gain to limit the x-ray dose. Industrial components, however, require a greater image contrast than medical images; therefore, the amplifier gain must be reduced. Higher resolution was achieved by using a larger output screen than on a typical medical image amplifier. The larger screen provided a 100% improvement in contrast and more than a 20% increase in resolution. A lens that enabled the system to operate in the high-contrast portion of the amplifier operating range resulted in very low magnification of the lens system. This allowed a complete silhouette of the amplifier image to appear within the monitor field, producing high-contrast image.

To produce high-quality video images, a high-resolution camera and digital image processing equipment are required. The AFWAL system uses several processing techniques to emphasize edges, adjust contrast, filter background images, and reduce noise. The digitized image can be stored on magnetic tape. Storage of digital images prevents the loss of image quality that often results with video recorders.

The final element of the AFWAL system is the parts handling equipment. One of the advantages of nonfilm radiography is the ability to view a part while it is in motion. This allows the operator to build a mental, three-dimensional image of the item under test. In-motion radiography also allows the operator to differentiate between anomalies in the system, which remain stationary, and features of the item under inspection, which move. The prototype system designed by AFWAL researchers for this project provides motion that is horizontal across the x-ray beam, vertical through the beam, parallel to the beam, and also provides rotation about the axis of the beam. The parts handling system also includes a robot to move parts to and from the system. The robot was particularly useful when a large volume of parts required inspection.

REFERENCES

Lowry, N. M., "High Resolution Nonfilm Radiography: Vol. 1 Executive Summary," AFWAL-TR-84-4125, Materials Laboratory, Air Force Wright Aeronautical Laboratories, September 1984.

3.5.5 LOW-ENERGY RADIOGRAPHY

Laboratory: Lawrence Livermore National Laboratory (LLNL)

Contact: S. Fletcher or J. Haskins
Lawrence Livermore National Laboratory
(415) 423-4267

LLNL is active in low-energy radiography, including energies as low as 3 keV. The objective of this work is threefold: first, to conduct experiments to characterize the effects of film processing, tubehead and power supply design on image quality using various radiographic films in the low- and ultra-low-energy range (3 to 50 kV); second, to characterize and relate x-ray energy spectra to radiographic quality; and third, to determine the benefits of using various alloy and element specific targets. The work in low-energy radiography is also investigating the benefits of using alloy and nonconventional materials as x-ray tube targets in the low-energy range.

Several important benefits have been derived from this research. The first is the knowledge of which target materials give better contrast or better penetration. A second benefit is increased parameter control and ability to quickly determine the technique that will optimize desired characteristics of a part using the understanding of the characterization of the low- and ultra-low- (less than 50-kV) energy radiography. This is especially applicable to the program that sees a variety of sizes of low density parts. A third benefit is the continued use of equipment that was built to perform the low-energy radiographic parameter research, the "Low-Energy Radiographic Unit" with its flexibility in changing many radiographic parameters quickly and easily. The ability to maintain a Helium flight path minimized the attenuation and scatter otherwise encountered with a flight path of air, thereby obtaining a truer response to changes in the other parameters. This unit will be available for further research and program use.

REFERENCES

Fletcher, J., and J. J. Haskins, "Characterization of Radiographic Variables in the Ultra-Low to Low Energy Range (5-50kV)," Annual Report for Engineering Research Program in the M. E. Department for October 1984-September 1985, September 1985.

3.5.6 MATERIALS CHARACTERIZATION WITH SMALL-ANGLE NEUTRON SCATTERING

Laboratory: National Bureau of Standards (NBS)

Contact: Charles J. Glinka
Center for Materials Science
(301) 921-3634

Small-angle neutron scattering (SANS) is a relatively new NDE technique that has become an important tool in materials characterization. Because SANS can examine a large volume of material (approximately 1 cm^3), it yields information on bulk properties, such as the size, shape, and volume fraction of structural inhomogeneities. Applications include the characterization of carbide precipitates and voids in high-temperature ferritic steel (Kim et al. 1983), and the analysis of microcracks in bulk ceramics (Case and Glinka 1984).

A highly collimated beam of low-energy (long-wavelength) neutrons is used as a material probe in a SANS experiment. The neutrons are generated in the NBS Research Reactor, an enriched uranium, heavy-water moderated reactor that operates at 20 MW and produces a peak thermal neutron flux of 4×10^{14} neutron/cm²/s.

With this neutron beam, specimens of 5 to 10 mm thickness can be investigated. The neutrons penetrate the material, producing a diffraction pattern that is detected by a large ($65 \times 65 \text{ cm}^2$), two-dimensional, position-sensitive proportional counter (see Figure 3.5). Microstructural information is derived

FIGURE 3.5. Schematic Diagram of Apparatus Used for Small-Angle Scattering Experiments (Case and Glinka 1984)

by comparing the measured angular distribution of the scattered neutrons with calculated scattering curves based on an appropriate model for the scattering centers (i.e., the structural inhomogeneities) (Case and Glinka 1984).

The technique is sensitive to features in the size range 10 to 1000 Angstroms, with some sensitivity up to 0.1 micrometers. A new cold neutron source, a 25-Liter D₂O moderator cooled to 30 K (to be installed this year), will enrich the beam in longer wavelength neutrons and thus extend the upper size limit sensitivity. The higher neutron fluxes afforded by this new source will allow in situ, real-time studies (10 to 100 s) of precipitation and void formation in a wide variety of bulk structural alloys.

In metallurgy, SANS is being used to study changes in alloy microstructure after thermal and mechanical treatment. NBS researchers, in association with researchers at Northwestern University and ORNL, have completed an investigation of carbide precipitation in a ferritic stainless steel (Fe9Cr1Mo)-- a high-temperature alloy proposed as replacement for austenitic steel in certain power generation applications. SANS results showed that large numbers of small carbides were associated with maximum hardness. SANS was also able to detect microstructural changes in a deformed sample after only a few hours of fatigue (Kim et al. 1983).

Application of SANS to NDE and process technology are only beginning to be developed. SANS could be applied to the detection and characterization of delaminations, defects, and microcracks in graphite composites. Another important area of potential applications is the use of SANS to monitor the in situ processing of ceramic materials. Work is expected to progress as soon as the cold neutron source is installed (Hardman-Rhyne, Robbins and Fuller 1984).

Work is progressing using SANS as a basis for comparison with other NDE techniques such as ultrasonics and AE (Wadley and Glinka 1984). The SANS facility is available for collaborative use (through the NBS Research Associate Program) or for independent use on a time/cost basis. The SANS facility is heavily utilized. Proposals are reviewed by a SANS scheduling committee, that examines the merit and conditions of each application.

REFERENCES

- Case, E. D., and Glinka, C. J. "Characterization of Microcracks in YCrO_3 Using Small Angle Neutron Scattering and Elasticity Measurements," Materials Science, 19, 1984, 2962-2968.
- Hardman-Rhyne K., C. Robbins and E. R. Fuller Jr. 1984. "Green State Ceramics," NBS Technical Activities 1984, 125-131.
- Kim, S. et al. "Microstructural Evaluation of a Ferritic Stainless Steel by Small Angle Neutron Scattering," Nondestructive Evaluation: Application to Materials Processing, O. Buck and S. M. Wolf, editors, Philadelphia, PA, October 1983, 169-176.
- Wadley, H. N. G. and Glinka, C. J. "Small Angle Neutron Scattering Study of Precipitates in Carbon Steel," NBS Technical Activities 1984, 133.
- "Facilities of the National Bureau of Standards," NBS Special Publication 682, NBS, Washington, D.C., September 1984, 5.
- "NBS Center for Cold Neutron Research," Presentation by NBS to the National Research Council, National Academy of Sciences, March 18, 1984.

3.5.7 MICROFOCUS ROD-ANODE X-RAY UNIT DEVELOPMENT AND APPLICATION

Laboratory: Oak Ridge National Laboratory (ORNL)

Contact: B. E. Foster
Nondestructive Testing Group
(615) 574-4837

The need to examine tube-to-tubesheet welds in steam generators has led to the research and development of small-diameter microfocus rod-anode x-ray units. ORNL personnel have cooperated with commercial developers of the device to obtain units that meet the required design criteria. They have refurbished four production x-ray units used by the Westinghouse Nuclear Components Division (W-NCD) for manufacturing examination of the steam generators at the Clinch River Breeder Reactor. Technical support to W-NCD was also provided for the final stage of training of personnel in the operation of the microfocus x-ray equipment.

Rod-anode x-ray systems consist of a high-voltage source for generating and accelerating an electron beam and a cylindrical arm through which the electron beam is transmitted. The beam target (and source of x-rays) is located at the end of the arm. The arm, or anode, can be inserted into holes or openings in specimens that require high-resolution radiography or have limited access for placement of the radiation source. These units have been used primarily at ORNL to examine tubing and welds where tubing joins other materials when access for the x-ray was limited to the tube bore, and to inspect the welds in steel tanks with access only through small-diameter openings.

The x-ray unit is operable to 150 kV with interchangeable small-diameter anodes and targets. Anodes with diameters as small as 9 mm (0.36 in.) and lengths of 1550 mm (60 in.) have been fabricated and used. A focal spot size of 0.1 mm (0.004 in.) allows high-resolution radiographs to be made even for small values of source-to-film distance. An electromagnetic lens system allows monitoring and control of the beam to assure proper focusing and centering on the target.

REFERENCES

- Foster, B. E., "A Microfocus Rod-Anode X-Ray Unit and Applications," abstract from presentation given at "ORNL Technology Transfer Meeting: Emerging Advances in Nondestructive Testing", November 16-18, 1982.

3.5.8 NBS CENTER FOR COLD-NEUTRON RESEARCH

Laboratory: National Bureau of Standards (NBS)

Contact: Robert S. Carter
Reactor Radiation Division
(301) 921-2421

According to a recent report by the Major Materials Facility Committee of the National Academy of Sciences, the U.S. lags far behind other industrialized nations in the availability of cold-neutron measurement technologies (NBS 1984b). Facilities in Western Europe, notably the Institute Laue-Langevin (ILL) in France, have lead the way in cold-neutron research, and a major new facility in Japan has been funded. Currently, only Brookhaven National Laboratory (BNL) in the U.S. has some, albeit limited, cold-neutron research capability at its high flux research reactor.

To meet this immediate national need, NBS has developed a large-volume cold neutron source soon to be installed in its 20-MW Research Reactor. In addition, they are proposing to build a new 240 x 130 ft experimental hall, "guides" to transport the cold neutrons from the source to the hall, and at least 11 fully equipped experimental stations for advanced cold-neutron research. This \$25 million facility will be a national cold-neutron research center, available to all U.S. researchers on an equal basis (NBS 1984b).

The NBS Research Reactor is an enriched uranium, heavy-water moderated reactor that operates at 20 MW and produces a peak thermal neutron flux of 4×10^{14} neutrons/cm²/s (NBS 1984a). The 25-L, helium-cooled (to 30°K) D₂O cold-neutron source will be installed in the reactor as shown in Figure 3.6. Preliminary calculations indicate this source will increase the cold-neutron flux by an order of magnitude.

Cold neutrons have wavelengths in excess of 4 Å. These neutrons have lower velocities, thus lower energies, than thermal neutrons. The lower energy allows observation of larger features, such as voids and microcracks, in neutron scattering experimental applications. Another advantage of cold neutrons is that they can be precisely focused and easily transported by "optical"

FIGURE 3.6. Geometry of Current NBS Cold-Neutron Source (NBS 1984b)

devices. This will aid the development of ultra-high resolution spectrometers and other new cold-neutron measurement technologies.

Cold-neutron research is expected to advance basic science and improve technological applications in four major disciplines: physics, chemistry, materials science, and biology. Applications in materials science should be strong, especially in the fields of polymer research, metallurgy, and ceramics. SANS has been instrumental in furthering the fundamental understanding of polymer structures. In metallurgy, SANS has been used to study changes in alloy microstructure after thermal and mechanical treatments, which has helped provide new insights into both the processing and in-service degradation of commercially important materials (NBS 1984b).

With cold neutrons, SANS techniques will have extended range (ability to detect larger features) and higher resolution. In addition, the higher flux

(rate of neutron delivery) will allow in situ, real-time studies of precipitate and void formation in bulk structural alloys (NBS 1948b).

Applications in both NDE and processing technology are expected. Preliminary work correlating neutron scattering techniques with other more conventional, NDE techniques, such as ultrasonics and AE, is being conducted by C. J. Glinka (Reactor Radiation Division, 301/921-3634).

Researchers in the Ceramics Division at NBS have already begun developing theoretical and experimental measurement techniques to monitor ceramics production processing. With cold neutrons, they expect to be able to study the in situ densification process, from green-state compact to fully sintered ceramic (contact: E. J. Fuller, Jr., 301/921-2842).

The Center will operate as a national user facility, with two modes of development: at least ten experimental stations will be developed by NBS; five additional stations will be developed for specific research teams from organizations outside the U.S. A Program Advisory Committee (PAC) will schedule a large percentage of the time on these stations on the basis of written proposals and scientific merit. With continued funding, the Center should be completed by 1989 (NBS 1984b).

REFERENCES

"Facilities of the National Bureau of Standards," NBS Special Publication 682, NBS, Washington, D.C., September 1984a.

"NBS Center for Cold Neutron Research," presentation by NBS to the Major Materials Facilities Committee, National Research Council, National Academy of Sciences, March 1984b.

3.5.9 RADIOGRAPHY AND COMPUTER TOMOGRAPHY CAPABILITIES

Laboratory: Sandia National Laboratories (SNL-A)

Contact:	O. J. Burchett	or	B. D. Hansche
	Supervisor, Nondestructive		Division 7551
	(505) 844-3500		(505) 844-3500

SNL at Albuquerque has important and distinguished capabilities in radiography that are of potential interest to industry. SNL-A is active in micro-focus, flash and real-time radiography, in fluoroscopy, and in computer tomography. The level and quality of computer tomography work is especially noteworthy. Developments in radiography could be used to define the capability of various technologies and could be used as feedback to commercial vendors to provide information on performance and improvements. Information on the capabilities and applications of computer tomography could help in speeding the transfer of radiography technology, which is developing rapidly, in industrial areas.

For example, SNL-A has designed, built, and is developing a fan-shaped 32 detector array for computer tomography work with microfocus and other x-ray generators (10 to 300 kV). The array has slit openings of 0.02 in. When used with Sandia's microfocus x-ray system a projection of 0.002-in. spot size is expected. SNL-A staff have designed the array head and are assembling the detector and electronic amplifier electronics. The tomographic array is believed to have capabilities beyond commercial systems available to industry.

Other advanced radiography development and facilities at SNL-A include:

- detector array for 2.5-MeV linear accelerator (31-element array acquired from Scientific Measurement Systems)
- film radiographic tomographic reconstruction procedures for 10 MeV linear accelerator
- microfocus x-ray systems for high-resolution imaging
- software for color image density-gauging (DXT).

3.5.10 RADIOGRAPHIC DETECTABILITY LIMIT RESEARCH

Laboratory: NASA Lewis Research Center (LeRC)

Contact: George Y. Baaklini
(216) 433-6019

The strength-limiting defects commonly observed in sintered silicon-base ceramics such as SiC and Si₃N₄ include pores, microcracks, inclusions, and variations in the microstructure. During the fabrication process inclusions are introduced, and pores and microcracks are formed. X-radiography can be used as an NDE tool to detect and identify these flaws. However, the limits of x-ray detectability of defects have to be evaluated and proven applicable to defects that cause fractures and limit strength (critical size defects) in sintered structural ceramics. The ability to detect voids in structural ceramics is vital for better and more reliable ceramics.

LeRC studies have compared the reliability of two different x-radiographic techniques in finding seeded voids in green and sintered silicon carbide (SiC) and silicon nitride (Si₃N₄). Seeded test bars of SiC and Si₃N₄ were examined using conventional and microfocus x-radiographic techniques. Both surface and near-surface voids of varying sizes were created in the test samples. Unambiguous foreknowledge of the actual size and location of each void was essential to establish probability-of-detection statistics in the silicon carbide and silicon nitride test bars and to render an accurate, quantitative comparison of the relative sensitivities of the two x-ray techniques studied.

The conventional x-ray system with a tungsten target and a 400-μm focal spot was operated in the 25- to 75-kV range with a beam current range of 5 to 8 mA. Test bars were positioned 92 cm from the source of radiation and in direct contact with the x-ray film. The exposure varied from 5 to 12 min.

The microfocus x-ray system with a molybdenum target and a 10-μm focal spot was operated in the 30- to 60-kV range with a beam current range of 0.25 to 0.32 mA. Test bars were positioned between the source and the film detector to produce an x-ray image with a magnification of approximately

2.5 times and with overall source-to-film distance equal to 30 cm. The exposure varied from 10 to 20 min. Figure 3.7 shows the radiographic techniques.

The ceramic specimen preparation technique was successful in creating seeded test bars with properties identical to those of typical SiC and Si_3N_4 materials (i.e., same density, composition, surface roughness, etc.). The seeding process did not introduce any other undesirable defects. The seeding process reliably produced uniformly sized surface voids. However, more research is needed to understand the effect of sintering conditions on the material surrounding the craters in the Si_3N_4 specimens. Further studies should attempt to optimize the forming of hemispherical craters.

The seeded internal voids were identical to typical naturally occurring voids. It was difficult to fully characterize these seeded internal voids; therefore, they were considered to be inappropriate for establishing reliability statistics. Consequently, only the specimens containing fully characterized surface voids were used to study the reliability of void detection for the two techniques used.

FIGURE 3.7. Conventional Contact Radiography and Projection Microfocus Techniques (Baaklini, Kiser and Roth 1984)

LeRC research demonstrated that microfocus projection radiography enhanced void detectability over conventional contact radiography. Thickness sensitivity improved by 2% in the green material and by 1% in the sintered material. This improvement was attributed to several factors: 1) smaller focal spot size, 2) projection method, 3) target material, and 4) softer radiation. However, soft x-rays would preclude examination of thick samples and would extend the exposure time needed to form the radiographic image. Also, in the projection mode the area available for specimen examination is reduced. More effort and time are needed, therefore, to evaluate ceramic specimens by microfocus radiography than by contact conventional radiography with its relatively hard x-rays.

The results suggest the use of void detection in green structural ceramic materials to help eliminate extra operational costs by rejecting unsuitable green parts. Furthermore, ceramic specimens of the green and sintered material with seeded voids, similar to the ones developed in this research, can be used as standards to evaluate the image of subsequent radiographs.

REFERENCES

- Baaklini, George Y., J. D. Kiser and D. J. Roth, "Radiographic Detectability Limits for Seed Voids in Sintered Silicon Carbide and Silicon Nitride," prepared for The Regional Meeting of the American Ceramic Society, San Francisco, California, October 28-31, 1984.

3.5.11 RADIOGRAPHIC MATERIALS CHARACTERIZATION SYSTEM

Laboratory: Lawrence Livermore National Laboratory (LLNL)

Contact: J. Haskins
Lawrence Livermore National Laboratory
(415) 423-4267

An impressive computerized system at LLNL applies existing radiographic technology. Its purpose is to optimize the utilization of technology and to permit easy customization by and for various end users. The system collects radiographic, gauging, physical parameter, and other data. These data are then integrated to provide a composite assessment of the quality of various parts and components. The system is menu driven and is continually upgraded (Figures 3.8 and 3.9).

Most of the radiation inspection results at LLNL can be presented in a computerized, image format through the system. The image enhancement part of the system, Image Manipulation Processing System (IMPS), provides edge and contrast enhancement, zoom, color and filter capability. A description of user friendly software for this computerized analysis system will be made available when it is completed.

FIGURE 3.8. Materials Characterization System at LLNL

FIGURE 3.9. Data Flow Diagram for Materials Characterization System

3.5.12 RESEARCH INVESTIGATIONS IN INDUSTRIAL RADIOLOGY

Laboratory: National Bureau of Standards (NBS)

Contact: C. E. Dick or J. W. Motz
X-Ray Physics Group
(301) 921-2201

The NBS X-Ray Physics Group has the following research projects in industrial radiology:

- X-Ray Imaging Systems Employing Digital Energy Subtraction Technologies - By subtracting two images of a given object, such that each image is produced with a different x-ray energy, the image of a hidden structure may be enhanced because of the difference in the absorption properties of x-ray beams having different energies. For any given object, it may be necessary to select x-ray energy combinations that will maximize the difference signal for the structure of interest.
- Quasi-Monoenergetic Beams in The Region from 50 to 500 keV - To produce quasi-monoenergetic x-ray beams in this energy region with an energy spread of less than 25%, various combinations of kilovoltages, filters, and geometries are used, and extensive x-ray spectral measurements are required.
- Response of Metallic Screens to Monoenergetic X-rays - Monte Carlo calculations have given the numbers and energies of electrons emitted from metallic screens irradiated by monoenergetic x-rays. These data will be used to increase sensitivity of x-ray screen-film systems used in industrial radiology, and to optimize thickness of these screens for different x-ray sources.
- X-Ray Scatter Effects in Industrial Radiology - A Monte Carlo program has been developed to determine fraction of scattered x-rays emitted from materials with various atomic numbers and thicknesses. These data may be used to design imaging systems that minimize scatter effects in industrial radiology.

To carry out these programs, the NBS X-Ray Physics Group has invited industrial, academic and governmental organizations to sponsor research partners to participate in joint research projects. The research facilities available to carry out this program include industrial x-ray machines (250 KU and 300 KU), three electron accelerators (0.5, 1.5 and 4.0 MV), and a large collection of image-processing and x-ray detection equipment.

REFERENCES

Dick, C. E., and J. W. Motz. "Digital Energy Subtraction Imaging," NBS Technical Activities 1984, 1D8-109, Nov. 1984.

"NBS Seeks Partners for Research on Radiological Imaging," NBS Update, August 26, 1985.

3.5.13 RESIDUAL STRESS MEASUREMENTS WITH ENERGY DISPERSIVE X-RAY DIFFRACTOMETRY

Laboratory: National Bureau of Standards (NBS)

Contact: Masao Kuriyama
Center for Materials Science
(301) 9921-2986

When monitoring an industrial material for structural stability, it is necessary to evaluate the residual stresses within the material. X-ray diffractometry is the most accurate, quantitative method for measuring these stresses, but conventional x-ray diffraction techniques are limited to surface or near-surface measurements. However, energy dispersive x-ray diffractometry (EDXRD) is capable of detecting stresses in the interior of bulk materials (Black et al. 1984).

M. Kuriyama of NBS has demonstrated the potential of EDXRD for the in situ evaluation of residual stress. Several years ago, he successfully mapped the distribution of strains across a weld zone in a section of Alaskan pipeline (Bechtoldt 1982). Areas of future application will include in-process quality control of heat treatment or cold-working steel operations.

When materials are under stress, x-rays diffract with a Bragg angle that is different from the Bragg angle in unstressed materials. The change in the Bragg angle is related to changes of atomic interplanar spacings in the material (Kuriyama, Boeltinger and Burdette). In conventional x-ray diffractometry, monochromatic x-rays impinge upon the sample surface at an angle θ and the detector is placed at an angle 2θ with respect to the incident beam (Bechtoldt 1982; Black et al. 1985). This angle is then varied by moving the apparatus about the sample. By analyzing the diffraction pattern, the strain components at the surface are determined.

In EDXRD, the sample and apparatus are both stationary. A multi-energy, or white, x-ray beam probes the sample. Changes in the atomic interplanar spacings are detected by energy-sensitive semiconductor detectors as peak shifts in the energy spectral profile. High-energy x-rays, up to 250 keV, can

be used to penetrate thick material (e.g., up to several centimeters of steel). With the NBS system, residual stress measurements have been made with a resolution of 1000 psi.

Research is under way to develop the system's capability to perform three-dimensional strain measurements through the thickness of a sample. Previously, the sample was scanned by the x-ray probe and translated in two orthogonal directions with respect to the incident beam, thereby averaging the thickness (Bechtoldt 1982; Black et al. 1985). Through-the-sample strain measurements would be advantageous for rapid on-line, in situ applications.

The strain gradient through a 9.5-mm-thick cantilevered steel bar was recently measured through the sample thickness (Black et al. 1985). Qualitatively, results compared very well with theory. Spatial resolution may be increased with further reductions in probe volume. Improvements in detectors and x-ray sources are expected and will be incorporated into the EDXRD system. Data acquisition time should improve dramatically with these modifications.

REFERENCES

- Bechtoldt D. J., et al. "X-ray Residual Stress Mapping in Industrial Materials by Energy Dispersive Diffractometry," Advances in X-ray Analysis, J. C. Ross, et al., eds., 329-338, NY: Plenum Publ., 1982.
- Black D. R., et al. "3-Dimensional Strain Measurements with X-ray Dispersive Spectroscopy," J. Nondestructive Evaluation, Vol. 5, No. 1. March 1985.
- Black D. R., et al. "X-ray Strain Measurements with Energy-Dispersive Spectroscopy," NBS Technical Activities 1984, 110-111, November 1984.
- Kuriyama M., W. J. Boettinger and H. E. Burdette, "X-ray Residual Stress Evaluation by an Energy Dispersive System," Proc. Symp. Accuracy in Powder Diffraction, NBS Special Publ. 567, 479-487, 1979.

3.5.14 TOMOGRAPHIC DENSITOMETRY

Laboratory: Idaho National Engineering Laboratory (INEL)

Contact: J. R. Fincke
Principal Investigator
Applied Optics
(208) 526-2031

A gamma-ray source, multiple detectors and a tomographic data reduction technique have been used to obtain density distribution of material flow in pipes. Examples of applications are in pressurized water reactors, two-phase flows, and pipeline coal transport for fossil fuel programs.

3.5.15 X-RAY TOMOGRAPHIC SYSTEM DEVELOPMENT

Laboratory: Los Alamos National Laboratory (LANL)

Contact: Dana Elliot Mike Price
 (505) 667-6291 (505) 667-1973

One of the major activities at LANL involves the development of an x-ray tomographic system for flaw characterization and density gauging. Although tomographic systems and methods are researched at several national laboratories, the work at Los Alamos verifies that x-ray or gamma-ray tomography has many potential industrial applications. The information, techniques, reconstruction software, and applications under development can be used as the engineering data base for demonstration and transfer of this technology to equipment manufacturers and industry.

A particular method of density gauging involves the coefficient of thermal expansion of the material being studied. Data collected at several different temperatures of a specimen with a known thermal expansion coefficient can be used to calibrate the system as a function of specimen density. This allows the interpretation, with regard to density and uniformity, of the data collected from other specimens of the same material.

3.6 THERMAL METHODS

3.6.1 EARLY CORROSION DETECTION OF STEEL UNDER PROTECTIVE COATINGS USING THERMAL-WAVE IMAGING

Laboratory: National Bureau of Standards (NBS)

Contact: Tinh Nguyen
Center for Building Technology
(301) 921-3208

Thermal-wave imaging is a recently developed NDE method that can detect image surface and subsurface defects at a higher resolution than conventional optical, x-ray, or acoustic probes. Lattice disruptions from the addition of one foreign ion in 10³ lattice ions can be successfully detected with thermal-wave techniques (Rosencwaig 1982). Because of this sensitivity, thermal-wave imaging has found considerable application in the semiconductor industry.

One aspect of NBS thermal-wave imaging work assesses its feasibility for detecting and characterizing corrosion and delaminations in steel under protective film coatings. The current corrosion detection method involves visual inspection, either through the coating (when clear) or after destructively removing the film. The early detection of corrosion and delamination by a nondestructive method is very important in the area of advanced composites and electronic materials and packaging (Yolken and Morfdin 1984).

The numerous methods of generating and detecting thermal waves leads to a wide variety of experimental configurations (MacLachan et al. 1985). In all cases, however, heat is introduced into a solid sample using a periodic heating source such as a modulated laser beam, electron beam, or ion beam. The periodic changes in local temperature set up a thermal wave that propagates through the solid and decays exponentially with distance. The rate of decay is dependent on the thermal diffusion length of the solid, which is a function of thermal conductivity, heat capacity, density, and beam modulation frequency. Therefore, the propagation of thermal waves is sensitive to local variations in thermal properties. Such local variations may arise from a variety of structures such as cracks, defects, delaminations, microstructure, and dopant concentrations. These can be accurately mapped through imaging of the thermal waves.

Researchers use a thermal-wave (Model 101) attachment to a 520 Hitachi Scanning Electron Microscope (SEM) with modulated frequencies in the range of 100 to 500 KHz (Nguyen and McKnight 1984). A piezoelectric transducer mounted beneath the sample detects the thermal waves. The output of the detector is amplified and used with the scan generators of the SEM to produce images on the SEM CRT.

In a recent experiment, rough and polished low-carbon steels with and without protective coatings were examined. Noncorroded and artificially corroded areas of the specimens were probed with the thermal-wave microscope, and results were compared with those from conventional optical and back-scattered electron microscopes. The thermal-wave microscope successfully imaged the microstructure of the metal under a 3- μ m-thick organic coating; the others could not.

Additional studies will examine the effects of various parameters, such as thickness and type of coating, size and concentration of pigments, and degree and type of corrosion. Work is also planned on thermal-wave imaging of delaminations under protective coatings.

REFERENCES

- MacLachan, J. W., et al. 1985. "Linear Thermal Wave Imaging," Second Conference Nondestructive Testing, Vol. 1, 441-448.
- Nguyen, T., and M. E. McKnight. "Nondestructive Early Detection of Corrosion and Delamination Under Protective Coatings, Using Thermal-Wave Microscopy," NBS Technical Activities 1984, 17-20, November 1984.
- Rosencwaig, A. "Thermal-Wave Imaging," Science 218, 223-228, 1982.
- Yolken, H. T., and L. Morfdin. "Strategic Plan for Nondestructive Evaluation, 1984-89," Office of NDE, NBS, December 1984.

3.6.2 THERMAL-WAVE IMAGING OF SURFACE AND NEAR-SURFACE DEFECTS IN CERAMICS

Laboratory: National Bureau of Standards (NBS)

Contact: Grady S. White and Lorretta Inglehart
Center for Materials Science
(301) 921-3277

A new NDE method, thermal-wave imaging, exceeds the resolution provided by conventional optical, x-ray and acoustic probes. Images with a spatial resolution of a few thousand Angstroms have been achieved in the detection of image surface and subsurface defects. Applications have been numerous in the semiconductor industry. Work by G.S. White and L. Inglehart is aimed at applying thermal-wave imaging to the detection and characterization of defects in ceramics.

Several methods for generating and detecting thermal waves lead to a variety of experimental configurations (MacLachan et al. 1985). However, in all methods, heat is introduced into a solid sample using a periodic heating source such as a modulated laser beam, electron beam, or ion beam. The periodic changes in local temperature create a thermal wave that propagates through the solid and decays exponentially with distance. The rate of decay is dependent on the thermal diffusion length of the solid, which is a function of thermal conductivity, heat capacity, density, and beam modulation frequency. Therefore, thermal wave propagation is sensitive to local variations in thermal properties. These local variations may result from structures such as cracks, defects, delaminations, microstructure, and dopant concentrations, which can be accurately mapped through imaging of the thermal waves.

In their investigations of defects in ceramics, NBS researchers use a photoacoustic cell to detect thermal waves. A photoacoustic cell is a closed cell filled with a gas. The sample is placed inside, and a laser beam modulated in the frequency range 10 to 200 Hz periodically heats the sample. Surface temperature oscillations produce gas pressure variations, that are detected with a sensitive microphone.

Aluminum-oxide ceramic specimens with defects from 0.6 to 1.0 mm were recently studied with this technique (White, Fuller and Jones 1984).

Indications of all three defects were observed; however, the smallest one (0.6 mm) approached the resolution limit of the system. Modifications are under way to improve the resolution, including decreasing the volume of the cell and increasing the microphone sensitivity. With these and other modifications, a spatial resolution of 300 μm is expected. This is closer to the resolution required for a process-control sensor applicable to ceramics production.

REFERENCES

- MacLachan, J. W., et al. 1985. "Linear Thermal Wave Imaging," Second Conference Nondestructive Testing, Vol. 1, 441-448.
- White, G. S., E. R. Fuller and M. Jones, "Thermal-Wave Examination of Surface and Near-Surface Defects in Ceramics," NBS Technical Activities 1984, 12-15, November 1984.

3.7 ULTRASONICS METHODS

3.7.1 ACOUSTOELASTIC MEASUREMENT OF STRESS AND TEXTURE

Laboratory: Ames Laboratory (Ames)

Contact: R. B. Thompson
(515) 294-7803

This program at Ames focuses on the nondestructive measurement of residual stress, specifically the experimental verification of an acoustoelastic technique for measuring residual stresses in materials of unknown microstructure.

The basis for this technique is a prediction of continuum mechanics that states that the residual stresses in a textured material of unknown microstructure can be determined from the relationship

$$\sigma_{ii} - \sigma_{jj} = 2 \rho V_{ij}^0 (V_{ij} - V_{ji})$$

where V_{ij} is the velocity of an ultrasonic shear wave propagating in the i -direction and polarized along the j -direction, the superscript zero denotes its stress-free value, ρ is the density, and σ_{ii} and σ_{jj} are principal stress components. Derivation of this equation assumes that the textured material has a macroscopic orthorhombic or related symmetry and that the axes of principal stresses coincide with the material symmetry directions. Under these assumptions, the equation predicts that only the material density and the velocities of two shear waves, whose directions of propagation and polarization have been interchanged, must be known to determine the principal stress difference (V_{ij}^0 may be approximated by V_{ij} due to the small magnitude of the velocity shifts). The only material property that enters this relationship is the density, which is relatively insensitive to microstructure.

Several experiments with aluminum polycrystals were performed to provide data on the possible use of the above prediction for measuring stress. In experiments with plate samples (0.5 to 1 mm thick and approximately 40 cm on a side) ultrasonic waves polarized in the plane of the plate (known as SH or horizontally polarized shear waves) were excited by a pair of EMAT transducers requiring no couplant. The SH waves have the same velocity as plane waves in an infinite medium. When the transducers are held at fixed separation by a

rigid spacer, the angular dependence of the shear wave velocity, including as a special case the two velocities required for application of the previously cited equation, can be measured.

A 6061 Al plate was used to test the ability of the technique to suppress the effects of weak anisotropy. Measurements of an unstressed commercial grade plate showed a maximum SH wave velocity change of 0.15% between waves propagating along the rolling direction and at 45° with respect to this direction. Although small, this value is comparable to the stress-induced velocity shifts and represents one of the fundamental limits to inferring stress from ultrasonic velocity measurements. From the velocities of SH waves propagating parallel and perpendicular to the rolling direction, the equation allowed stress to be absolutely predicted in the presence of this anisotropy. With no adjustable parameters, errors were 20 MPa (3 ksi) or less, which is more than an order of magnitude less than the yield stress and an encouraging result.

A plate of 1100 Al was used to test the ability of the technique to suppress the effects of plastic deformation. Although sharp breaks in plots of velocity versus stress for the two individual SH modes occurred at the yield point of 55 MPa, their difference continued to vary linearly with stress in the plastic regime. Furthermore, the stresses predicted during loading and unloading were quite close, compared with the behavior of the individual velocities. Errors were of the same magnitude as in the 6061 Al experiments; however, stress was overestimated in the 6061 Al and underestimated in 1100 Al.

A theoretical analysis to determine what occurs when principal stress direction and material symmetry directions do not coincide agreed with the experiments on Al 6061. Successful verification in a range of materials would significantly expand the generality of the approach.

Further extension of the theory showed that the data can also be used to characterize texture. The first four coefficients of the expansion of the crystallite orientation distribution function can be deduced from the measurements. Thus, directional variation of the mechanical properties of rolled materials can be predicted.

3.7.2 ADVANCED ULTRASONIC INSPECTION INSTRUMENT

Laboratory: Pacific Northwest Laboratory (PNL)

Contact: Al Birks
Nondestructive Testing Section
(509) 375-2138

PNL has designed a modular ultrasonic NDE instrument for U.S. Air Force field and depot NDE activities. This advanced ultrasonic testing (UT) instrument was designed to incorporate the best state-of-the-art developments in ultrasonic transducers and electronic circuitry. It offers higher sensitivity, higher reproducibility of test results, and better maintainability than previously used Air Force ultrasonic NDE equipment.

To establish design specifications for a prototype model, contemporary commercial UT instruments were evaluated. An Ultrasonic Test Facility was assembled at PNL, and included the following components: oscilloscope, chassis, constant amplitude signal generator, peak detector, pulse receiver, tone burst generator, spectrum analyzer, low-capacitance probe, and oscilloscope camera. A block diagram of a typical ultrasonic instrument is given in Figure 3.10. Test points where performance data were monitored are labeled A through G.

Ten commercial ultrasonic instruments were evaluated. Seven were widely used models at Air Force NDI shops and at aircraft manufacturers. The other three were portable models new to the market. The PNL data indicated that significant performance differences exist between different instruments. Differences were complicated by the variety of interactive controls that were often unmarked and uncalibrated.

These evaluations confirmed that the ultrasonic NDE industry lacks uniform rules or guidelines for equipment design and performance. Electronic performance including the operation of pulser, receiver, and display circuitry, was found to vary greatly, even within the product lines of a individual manufacturers. The PNL design work therefore focused on the standardization of circuitry, performance, marking and identification of controls, and equipment set-up and calibration.

FIGURE 3.10. Block Diagram of Test Points in Typical Ultrasonic Instrument (Birks 1985)

In addition to their survey of commercial UT equipment, PNL examined advanced technical concepts to appraise the possibility of incorporating state-of-the-art developments in the Air Force NDE instrument. Concepts in advanced circuit design, signal processing, and noise reduction were reviewed. Improvements to the instrument design included a programmed microprocessor with solid-state memory to simplify the control settings for up to 50 inspection procedures, and a high-energy square wave pulser to control the test frequency and to improve the efficiency of transducer excitation (Birks 1985).

From a mathematical study of various pulse shapes, PNL found that the use of a square wave pulse of an appropriate period for a given test frequency provides a workable technical method for controlling the acoustic frequency of transducers. The circuit used to generate the square wave also has a buffering effect on the wave-shaping circuits, minimizing changes in frequency content of these signals. Consequently, the wide variation of load impedances exhibited by various piezoelectric materials and element sizes can be accommodated.

Six prototype models based on PNL design specifications were produced by two commercial manufacturers: Sonic Instruments, Inc., Trenton, NJ; and Systems Research Laboratories (SRL), Dayton, OH. These prototype units for field trials were essentially concept models, not production prototype models having

construction maturity and operational reliability. The prototypes were field tested by the AFWAL Manufacturing Technology Division. The objectives were to evaluate the models in terms of performance and reliability, and to obtain constructive comments and suggestions from equipment operators. The tests indicated excellent probability of detection of all defects. The probability of false detection was also significantly lower than with standard equipment (Birks 1985). A commercial version of the instrument is now being manufactured by Nortec.

REFERENCES

Advanced Ultrasonic Equipment, PNL, Research Results Information Sheet NDT-0300, n.d.

Birks, A. S. "Advanced Ultrasonic Nondestructive Evaluation Equipment," Report AFWAL-TR-84-4140, Feb. 1985.

3.7.3 AN AUTOMATIC ULTRASONIC DATA ACQUISITION SYSTEM

Laboratory: Sandia National Laboratories (SNL-A)

Contact: John Gieske
Division 1552, Ultrasonics
(505) 844-3500

State-of-the-art ultrasonic techniques for sizing defects have been inadequate. In some cases, the capabilities of defect sizing do not allow an accept/reject decision to be made. An annular phased array system is being developed for general NDE applications on metal and ceramic materials. The main usefulness of phased array techniques is the ability to electronically change the focus of the acoustic beam radiating from a phased array transducer or reflecting from a defect in a solid material.

The annular phased array system is part of a general purpose ultrasonic data acquisition and display system. A quick change from phased array operation to conventional single transducer operation is possible because the scanning motion of a single or multi-element annular array transducer is under complete computer control. After initiation of the system, data acquisition, storage and display of all acceptable echoes proceeds automatically. Cumulative real-time plots of the data are made during scans to allow the operator a preview of the data collected. When scanning of the target material is complete, appropriate B-scan and C-scan plots of the data at given threshold amplitudes can be made. C-scan plots of threshold amplitudes allow sizing by the annular array technique to be accomplished largely independent of defect depth and system gain.

Improvements in the programmable phased array controller are still possible. These may include faster RAM devices and improved techniques for delaying the receiver waveforms. Further work is planned to improve these techniques that should be beneficial for general NOE applications.

REFERENCES

Gieske, J. H., G. C. Stoker and P. D. Walkington. 1984. "Sizing Defects Using Annular Array Techniques with an Automatic Ultrasonic Data Acquisition System," In Review of Progress in Quantitative Nondestructive Evaluation, Vol. 3A.

3.7.4 AN ULTRASONIC THICKNESS GAUGE

Laboratory: Sandia National Laboratories (SNL-A)

Contact: William Shurtleff
(505) 844-3500

The light-emitting diode (LED) thickness gauge is a hand-held, real-time, ultrasonic image display for measuring thickness of materials. It is useful for multilayered structures and materials with rough surfaces and high attenuation.

The basic display is composed of a matrix of LED elements of i rows high and j columns wide. The threshold level of each i th row for the video waveform is 6dB above the i th-1 row, which provides a large dynamic range for signal strength from baseline noise. Each j th column of the LED matrix is set for increasing time delays representing equal increments of thicknesses of the material being examined.

The whole LED screen is composed of one upper and one lower basic display. The upper basic display indicates the position of the video waveform within a coarse range of thicknesses. The lower basic display shows a magnified view of the video waveform appearing in the j th column of the coarse display, as selected by the operator using a selection switch for the j th column of the upper display. A visual display of the entire ultrasonic video waveform is provided to the operator so that a hand/eye coordination is possible for maximizing signal strength by manually adjusting the ultrasonic probe. Measurement of thickness is provided by noting the thickness represented by the j th column of the lower LED display where the leading edge of the video pulse resides. Momentary flickering of the LEDs still provide thickness measurements as the operator manipulates the ultrasonic probe over rough surfaces. Measurement of the thicknesses of multilayer structures is possible by choosing corresponding multiple echoes of the video waveform as indicated by the upper coarse LED display with use of the selection switch. The two features, hand/eye

coordination of the probe with a quantitized thickness display and the possible measurement of multilayered materials, are not possible with other present-day digital ultrasonic thickness gauges.

REFERENCES

"Visit to Sandia National Laboratories, Albuquerque," November 1985

3.7.5 AUTOMATED MULTIVIEWING ULTRASONIC TRANSDUCER

Laboratory: Ames Laboratory (Ames)

Contact: D. O. Thompson
Program Director, Applied
NDE Programs
(515) 294-7803

In recent years, theoretical advances in inverse elastic wave scattering in the long and intermediate wavelength regimes have provided a basis for techniques to detect and characterize flaws in materials. To exploit these advances, researchers at Ames have developed an automated multiviewing ultrasonic transducer along with a first-generation signal processing program to determine the size, shape and orientation of flaws.

In the multiviewing transducer system, intended for water immersion use, six individual transducers are arranged in a hexagon around a central individual transducer. Each of the six peripheral transducers is placed in a gimbeled mount so that the angle of incidence (defined as the angle between the normal to the sample surface and the axis of the transducer) may be varied from 0° to 30° . The six transducers are then coupled to one drive system so that they can be set to the same angle ($\pm 0.25^\circ$) simultaneously. The angle is chosen so that the beams from the six peripheral transducers and the center transducer intersect along the axis of the center transducer at any depth in the sample material.

Electronic circuits have been assembled to activate the multiprobe using commercially available components wherever possible. A detailed data acquisition program provides automatic sequencing of the composite transducer and the acquisition of independent data records. After a flaw signal is found using the central transducer probe in a pulse-echo operation, the algorithm provides automatically for measurements to be made of other key set-up parameters that include the length of water path between the central transducer and the front surface of the sample and the depth of the flaw within the sample. These measurements are obtained by digitizing the elapsed time between the transmit pulse and the front surface reflection and flaw reflection, respectively. With

this information, the required angle of incidence for the side-looking transducers is computed and set. Following this step, the circuit switches to a pitch-catch mode that employs the central transducer in the transmit mode and each of the six peripheral transducers sequentially in a catch mode.

Thirteen independent pieces of information are acquired: pulse-echo responses on all seven transducers and six pitch-catch responses resulting from use of the central and peripheral transducers. The wave forms are then digitized and stored.

A first-generation set of post-processing data procedures has been developed and implemented for use with the new multiprobe instrumentation that provides a 3-D reconstruction and characterization of volumetric flaws (size, shape, orientation and acoustic impedance estimates). The program can be run either automatically from beginning to end with no operator intervention or by individual segments selected from a menu. This set of procedures represents the first step in the development of a structured decision-tree algorithm for flaw characterization.

Work continues to upgrade and extend the hardware and software capabilities of the multiprobe transducer and explore its capabilities in the reconstruction of naturally occurring flaws. Current or planned projects include the following:

- extending the experimental concept so that fixed and variable aperture operation is possible
- upgrading the electronics portion of the transmit-receive circuitry
- performing reliability and sensitivity analyses for incorporation into the overall signal processing algorithms
- further developing the decision-tree algorithm for flaw characterization
- further evaluating the instrumentation on real flaws (tests with weldments will be continued, tests with forged materials and materials sensitive to stress corrosion cracking are planned).

A new direction in development is toward a hybrid technology that uses the features of the new long-wavelength reconstruction (hardware and model-based algorithms) with high-frequency techniques such as Synthetic Aperture Focusing Techniques.

REFERENCES

Thompson, D. O., and S. J. Wormley. "Long and Intermediate Wavelength Flaw Construction," Review of Progress in Quantitative Nondestructive Evaluation, Vol. 4A, 1985.

3.7.6 AUTOMATED ULTRASONIC TEST BED

Laboratory: Lawrence Livermore National Laboratory (LLNL)

Contact: Jim Brase
Lawrence Livermore National Laboratory
(415) 422-6992

Two major causes of problems in the field of ultrasonic testing are the variety of shapes of parts to be tested and the variety of types of tests to be conducted. As a result, ultrasonic testing has been very time consuming and expensive compared to other NDT techniques.

The Nondestructive Evaluation Section of LLNL has designed and built an ultrasonic test bed (UTB) that overcomes the problems of other ultrasonic techniques. It combines a versatile mechanical system and a completely programmable motion control system. The UTB manipulates two transducers, which ensures maximum flexibility in the types of scans it can perform. Each of the two transducers is attached to the bottom of a vertical arm and each arm moves independently. To provide the capability for scanning rotationally symmetric parts, the test bed has two rotating spindles on which the test parts can be mounted.

When conducting ultrasonic tests, it is necessary to scan very large parts while detecting very small flaws. The UTB can handle parts up to 6 ft long and 4 ft in diameter but can move in increments as small as 0.0001 in. or 0.002°. To meet these accuracy and resolution requirements, the water temperature in the scanning tank and the air temperature in the room must be carefully controlled. The UTB is mounted on pneumatic isolators to shield it from external vibrations.

The user controls the test bed through a network of four LSI-11/23 computers, each dedicated to one portion of the control task: motor control, current transducer positioning and orientation display, manual remote control unit and system-user interface.

The task of motor control is to take a given set of 14 destination coordinates, one for each of the 14 axes of motion, and translate them into motor voltages necessary to produce the desired motion. Each movable axis must end

up at the correct destination coordinate, and a specified path must be followed to reach the destination. Each axis of motion is controlled by a separate microcomputer that is specially designed to handle path interpolation. This allows all 14 axes to move simultaneously, making it possible to follow very complex spatial contours with the two transducers.

The position system in the UTB can give the user the position and orientation of the transducer for each data point. It also allows the user to establish a coordinate system with its origin at any point within the working space of the UTB.

The system-user interface consists of three major components: a remote control unit that is used to manually position the transducers, a menu-based system for operating the UTB and a programming language for developing test pathways or trajectories. The remote control is primarily used to position the transducer for the start of a computer controlled test, but it can also be used to modify a trajectory during test execution. The UTB menu system is the major interface used for setting up and executing ultrasonic tests. The UTB programming language allows the user to develop trajectory programs to scan complex part shapes.

The UTB provides an extremely versatile mechanical scanning system that is adaptable to any test object geometry. Setup time has been sharply reduced for nonstandard shapes. The UTB has simplified ultrasonic testing so that it can now compete economically with other NDE methods. The key to using this technology is the signal processing software, which can be made available to interested parties. Assistance in using the software can be obtained through consulting with key individuals.

REFERENCES

Brase, J. et al., "An Automated Ultrasonic Test Bed," UCRL-90626, (Preprint prepared for submittal to Materials Evaluation) May 1984.

3.7.7 AUTOMATED WELDING NONDESTRUCTIVE EVALUATION

Laboratory: Idaho National Engineering Laboratory (INEL)

Contracts:	J. O. Bolstad	B. A. Barna
	Principal Investigator	Program Manager
	Process Diagnostics/NDE	Process Diagnostics/NDE
	(208) 526-1753	(208) 526-6124

The objective of this work, supported by the DOE's Basic Energy Sciences, is to sense and interpret, in real time, information from the welding process. Two methods currently under development are 1) a weld vision system that uses a pulsed laser and gated intensified camera to overcome ambient welding light, and 2) an ultrasonic system to interrogate the interior of the metal to characterize the molten weld pool geometry and flaw information. Both are examples of NDE sensors applied in hostile environments.

3.7.8 COMPUTER-AUTOMATED ULTRASONIC INSPECTION SYSTEM

Laboratory: Air Force Wright Aeronautical Laboratory (AFWAL)

Contact: Edward Wheeler
Project Engineer, Manufacturing
Technology Division, AFWAL/MLTM
(513) 255-5151

Standard ultrasonic inspection techniques used in industry today can involve tedious manual or semi-automated operations that make them incompatible with high-rate industrial production inspection requirements. However, with advances in digital computer technology and the rapid integration of this technology into both laboratory and production environments, the development of computer-aided ultrasonic inspection has become a reality. By reducing inspection costs through reduced inspection time, decreased inspector interaction and more efficient inspection record storage and retrieval, these automated systems are proving their value and indispensability in the manufacturing environment. Computer-automated ultrasonic inspection can increase inspection reliability, provide permanent inspection records that can be used to track part integrity during the life of the aircraft, and establish a structured data base for statistical analysis of inspection results.

Under the sponsorship of AFWAL, General Dynamics' Fort Worth Division developed a five-axis laboratory prototype Computer-Automated Ultrasonic Inspection System (CAUIS) to inspect complex airframe forgings. This prototype CAUIS was successfully demonstrated on small forgings in a laboratory environment.

The prototype clearly demonstrated the potential of computer-automated ultrasonic inspection. Near-net-shaped airframe forgings were inspected at scan speeds of more than 6 in./s, a large improvement over previous manual or semi-automated methods. Nevertheless, the system was a laboratory prototype. The benefits of a CAUIS had not yet been demonstrated in a production environment. For this reason, AFWAL awarded a contract to General Dynamics' Fort Worth Division to demonstrate the benefits of a CAUIS configured for production inspection of large graphite/epoxy composite skins for the F-16 tail assembly.

The CAUIS was designed to use computer control of a scanning bridge, to computerize the data acquisition process, and to incorporate a multiplexed multiple-element array transducer, all of which would provide for maximum scanning speed and system throughput. The benefits to be demonstrated by the production CAUIS were 1) increased inspection rates, 2) decreased inspection costs, and 3) increased inspection reliability.

Finally, a Nondestructive Evaluation Terminal (NET) was to be a central data collection/management/evaluation system not only for this particular CAUIS, but for any additional computerized ultrasonic inspection systems implemented in F-16 production.

The development of the production CAUIS included assembly and integration of the various subsystems (bridge, bridge drive electronics, bridge control microcomputer, ultrasonic unit, and master computer system), development of bridge control and data acquisition software, as well as integration of technologies developed during the CAUIS implementation program.

An ultrasonic transmitting/receiving linear array transducer operating in a time-multiplexed mode was also adapted and implemented on the CAUIS. The multiplexed linear array consists of the following system elements:

- ultrasonic multiple array transducer
- multiplexer/demultiplexer hardware required to switch the transmitted and received ultrasonic signals between transducer elements
- specialized digital interface required to control the multiplexer/demultiplexer hardware.

A NET was established as a centralized data collection and management system for the CAUIS. The NET will ultimately be linked to all computer-automated ultrasonic inspection systems used in F-16 production.

The NET has been interfaced with each CAUIS in the production network by a high-speed data link. This NET/CAUIS link facilitates automatic data collection and archival of all inspection results. The NET system provides sophisticated flaw evaluation capabilities. Also, as the NET collects data from the

CAUIS, it provides periodic quality assurance management reports and statistical analyses that can detect and even anticipate problem trends in the manufacturing process.

The incorporation of the multiple element array transducer provides a wide "paint brush" sweep of F-16 tail assembly composites. In addition, the CAUIS can follow the outline of varying shaped composites, although the present hardware/software design limitations allow only the inspection of flat parts. These combined features drastically reduce inspection time as compared to the existing ultrasonic immersion system.

When the CAUIS stations are upgraded to allow inspection of complex contoured parts, a related expansion in NET capability will be required to effect advanced display and evaluation capabilities for these contoured parts, capabilities that currently exist only for the near-planar parts.

REFERENCE

Reid, D. K., and G. J. Melven, "Computer-Automated Ultrasonic Inspection System," AFWAL-TR-84-4102, February 1985.

3.7.9 CONCURRENT ULTRASONIC WELD INSPECTION

Laboratory: Idaho National Engineering Laboratory (INEL)

Contacts:	J. A. Johnson	B. A. Barna
	Principal Investigator	Program Manager
	Process Diagnostics/NDE	Process Diagnostics/NDE
	(208) 526-9021	(208) 526-6124

In this recently completed project, sponsored by the DOE Office of Industrial Programs, INEL researchers developed an automated ultrasonic weld inspection system. Welds are inspected on a pass-by-pass basis with a high-temperature transducer assembly following closely behind a welding head and interrogating a partially completed weld shortly after solidification. The ultrasonic signals are digitized and analyzed using advanced pattern recognition schemes to sort out defect signals.

The intent is to find defects before they are covered by subsequent weld passes, thus allowing easy repair of defective welds. Otherwise, if welds are inspected after the welding operation is completed (e.g., using radiography), repair of defective initial pass welds requires the time and energy-intensive step of grinding out of the top layers of metal. Thick weldments, as found for example when welding the deck structure on ships, can require as many as 20 weld passes. Concurrent inspection allows the welding process to be stopped and defective welds repaired prior to resumption of welding.

REFERENCES

Johnson, J. A., N. M. Carlson and A. D. Watkins, "Weld Energy Reduction by
ing Concurrent Nondestructive Evaluation," EGG-MS-6843, May 1985.

3.7.10 CRACK CHARACTERIZATION

Laboratory: Idaho National Engineering Laboratory (INEL)

Contacts:	J. A. Johnson	B. A. Barna
	Principal Investigator	Program Manager
	Process Diagnostics/NDE	Process Diagnostics/NDE
	(208) 526-9D21	(208) 526-6124

The purpose of this project is to obtain a fundamental understanding of the effect of real ultrasonic transducer fields interacting with cracks, and to develop capabilities for measuring and characterizing fracture features such as crack-tip profiles, crack initiation sites, crack growth fracture mechanisms and plastic zone location. The principles involved deal with the sensing and analysis of elastic wave generation and interaction by and with standard piezo-electric and advanced acousto-optic noncontacting techniques. Fast (200 MHz) real-time computer-based data acquisition techniques are utilized.

REFERENCES

- Johnson, J. A., and B. A. Barna, "The Effect of Surface Mapping Corrections with Synthetic-Aperature Focusing Techniques on Ultrasonic Imaging," Sonics and Ultrasonics, Vol. SU-30, No. 5, September 1983.
- Barna, B. A., "Modeling of Real UT Transducer Field/Flow Interactions in Quantitative NDE," July 1984.

3.7.11 EVALUATION OF EFFECTIVENESS OF HEAT TREATMENT ON STRENGTH OF ALUMINUM ALLOYS

Laboratory: NASA Langley Research Center (LaRC)

Contact: Joseph S. Heyman
Manager, NDE Research Programs
(804) 865-3036

Processing errors by suppliers of high-strength aluminum alloys have resulted in the possible placement of soft aluminum in critical structures such as the space shuttle. A nondestructive technique for evaluating structural members in place was needed to assure initial structure viability and to locate regions of material suffering annealing resulting from re-entry or from processing irregularities. Only second-order elastic constants were previously considered but combining second-and third-order elastic constant measurements now offers the potential of characterizing aluminum heat treatment.

The ultimate strength and failure characteristics of aluminum alloys is determined by many properties, one of which is controlled in the last stage of material processing. During that stage, the metal is rapidly quenched from high to near ambient temperature, usually in a water spray or bath. High strength is achieved via high cooling rates; great care must be exercised during the quench process to obtain desired material properties.

A variety of test procedures are used to evaluate the strength of quenched aluminum; however, a new technique was needed to provide a more accurate, physically quantitative procedure. LaRC has developed a nondestructive approach to characterize quenched aluminum alloys based on the ultrasonic properties of the material.

Many researchers have tried to link ultrasonic velocity directly to material strength, but the measurement of velocity will not predict strength. It only provides a relationship between the modulus and the density of the material. The new approach is to evaluate material higher-order elastic terms to get closer to the real nonlinear behavior. The approach demonstrates that the material strength is directly related to the material's Gruneisen parameter--a physical parameter of the solid material equation of state.

To measure the higher-order effects, it is necessary to impart acoustic propagation parallel to the applied tensile load in initially isotropic materials and then to measure a combination of second- and third-order elastic constants. To effect change in the resonant frequency, the technique combines material elongation resulting from applied strain and change in acoustic velocity resulting from applied stress. The normalized frequency relates back to the Gruneisen parameter and was chosen, therefore, as the important parameter to study.

The pulse phased locked loop (P^2L^2) was used for the test technique. It has a resolution for a change in natural velocity of parts in 10^7 , which translates into better than 10^{-12} s (2×10^{-7} cm) in a 1 in.-thick aluminum sample. The P^2L^2 is a voltage-controlled device that allows the determination of small frequency changes to be made as the electrical circuit remains in equilibrium.

This technique appears to be directly applicable to the measurement of the elastic properties of other materials, such as titanium weld metal, which is significantly affected when welding procedures are not carefully controlled. In the future, LaRC plans to determine the degree of fatigue in materials using similar analysis.

REFERENCES

- Heyman, J. S., and E. J. Chern, "Characterization of Heat Treatment in Aluminum Based on Ultrasonic Determination of the Second and Third Order Elastic Constants," presented at IEEE 1981 Ultrasonic Symposium, NDE at NASA Langley, June 1985.
- Heyman, J. S., "Advanced NDE Technology for Materials Characterization," presented at DOD 1984 MTAG Test and Inspection Mini-Symposium, November 25-29, 1984, NDE at NASA Langley, June 1985.

3.7.12 FLAW CHARACTERIZATION WITH SCANNING LASER ACOUSTIC MICROSCOPY

Laboratory: NASA Lewis Research Center (LeRC)

Contact: Edward R. Generazio
(216) 433-6019

Scanning laser acoustic microscopy (SLAM) has received considerable attention in recent years as a promising NDE technique. SLAM is generally used for identifying the approximate position, size, shape, and depth of material flaws such as inclusions, voids, and delaminations. Materials inspected by the SLAM technique include electronic and structural ceramics. The acoustic image of a flaw depends on the roughness of the surface in which the flaw resides; therefore, inaccuracies can arise when the surface of the material under study is acoustically rough. For subsurface flaws the acoustic image often consists of a diffraction pattern rather than a facsimile image of the flaw. In this case it is especially difficult to characterize the flaws. Nevertheless, relationships have been implied between diffraction-dominated acoustic images of the flaws and their actual size and depth. LeRC has done two studies involving the use of SLAM. The first examined the effect of sample surface roughness on the sound direction within a material; the second examined the relationship between diffraction-dominated acoustic images of subsurface flaws and the characterizations of these flaws.

The basic operation of the scanning laser acoustic microscope is as follows: longitudinal sound waves are produced by a piezoelectric transducer and transmitted through a couplant (usually distilled water) to the sample. The angle of the transmitted sound in the sample is given by Snell's law. Upon reaching the side of the sample opposite the incident-sound source, the sound displaces the surface to produce a "dynamic ripple." To observe the ripple, a laser beam is scanned over the sample. The laser light, angularly modulated by the surface deformations of the ripple, is reflected to a photo detector and produces a real-time image on a video monitor. Material defects such as voids, inclusions, or density variations will cause visible variations of the video acoustic image.

To investigate the effect of surface roughness on sound direction, images were made through surfaces of various roughness of a microscopic crack etched on a glass plate. Surface roughness had a substantial affect on the direction of the refracted sound propogation; therefore, Snell's law is not generally applicable to even moderately rough samples. Accurate depth measurements could still be made, however, when the direction of refracted sound propogation was determined experimentally.

Acoustical Fourier transforms were created to study the relationship between the images created by subsurface flaws and the flaws themselves. It was shown that these acoustical transforms, though not identical, are directly related to two-dimensional digital Fourier transforms of objects that simulate the size and shape of subsurface flaws.

REFERENCES

Generazio, E. R., and D. J. Roth, "Quantitative Flaw Characterization with Scanning Laser Acoustic Microscopy," reprint from CP-2383, "Analytical Ultrasonics in Materials Research and Testing," conference held at NASA Lewis Research Center, Cleveland, Ohio, November 13 and 14, 1984.

3.7.13 FLAW DETECTION IN CONCRETE USING AN IMPACT-ECHO TECHNIQUE

Laboratory: National Bureau of Standards (NBS)

Contact: Nicholas J. Carino
Center for Building Technology
(301) 921-2648

Conventional ultrasonic methods have been difficult to apply to the NDE of concrete, because of problems with wave attenuation from scattering at the many mortar-aggregate interfaces. One method that shows promise is the pulse-echo technique. Since the early 1970s, pulse-echo has been successfully used for integrity testing of concrete piles. It has also been used to detect large structural flaws in concrete dams, and to measure the thickness of concrete pavements (Carino and Sansalone 1984).

There is no standardized method, however, of applying pulse-echo techniques to the general NDE of concrete structures. Except for costly and often cumbersome radiographic methods, the only routine method of flaw detection in concrete is the inspection of drilled core samples, which can also be quite expensive and time consuming. According to N. J. Carino at the Center for Building Technology at NBS, "there is an urgent need to develop a reliable non-destructive system for flaw detection (in concrete) that is economical and easy to operate" (Carino and Sansalone 1984).

As part of an ongoing effort to develop such a system, N. J. Carino has innovated a variation on the pulse-echo technique. Because a suitable transducer for pulse-echo testing in concrete is not currently available, an approach using mechanical impacts to induce stress waves in the concrete slab under test is used. This "impact-echo" technique utilizes a short impulse of mechanical energy generated by dropping a steel ball on the surface of the slab. The impact time is varied by using different diameter balls. A ball of 4 to 16 mm in diameter is most commonly used, dropped from a height of 20 to 30 cm.

The principle of pulse-or impact-echo techniques is the same as that employed by sonar systems in ships for sounding ocean depths (see Figure 3.11). Mechanical energy in the form of a short pulse is introduced into

FIGURE 3.11. Pulse-Echo Method for Flaw Detection in Concrete (Carino and Sansalone 1984)

the test medium at an accessible surface by the impact. As the resulting stress wave propagates through the medium, it is reflected by defects in the material, or by grain aggregate boundaries. A receiver coupled to the surface of the test object monitors these reflected waves, or echoes. The signals are displayed on an oscilloscope. The depth to the reflecting surface, the location of the flaw, is determined by echo travel time analysis (Carino 1984; Carino, Sansalone and Huse in press; Carino 1985).

Another innovation is the use of a flat frequency response detector. This detector was designed by NBS (Proctor 1982) and is commercially available through Industrial Quality, Inc., Gaithersburg, Maryland. The advantage of the detector is that the captured signal can be analyzed in the frequency domain, making it possible to isolate the larger interface reflections, such as flaws or defects, from the diverse mortar-aggregate interface reflections.

A test section of concrete, 2 x 4.5 x 0.5 m, containing several known interfaces has been examined using impact-echo. Good correlation was found between the various sizes, depths, and inclination known to exist and the

impact-echo results. Research is under way on fresh concrete to determine the start of setting as the material hardens, and preliminary results look promising.

Future work will focus on developing a standardized pulse-echo technique for flaw detection in concrete. Work will include: development of a low-frequency focused transducer for concrete, development of a broadband receiving transducer that is easy to couple to concrete, and the characterization of flaws by frequency spectrum analysis (Carino and Sansalone 1984).

REFERENCES

- Carino, N. J., and M. Sansalone, "Pulse-Echo Method for Flaw Detection in Concrete," NBS Technical Note 1199, National Bureau of Standards, Washington, DC, July, 1984.
- Carino, N. J., "Laboratory Study of Flaw Detection in Concrete by the Pulse-Echo Method," Proc. Int. Conf. on In Situ NDT Testing of Concrete, Ottawa, Canada, October 1984, in press.
- Carino, N. J., M. Sansalone and N. N. Hsu, "A Point Source-Point Receiver, Pulse-Echo Technique for Flaw Detection in Concrete," American Concrete Institute, to be published.
- Carino, N. J., "Impact-Echo Technique," CBT/RILEM Symposium on Advanced Flaw Detection Techniques for Concrete, National Bureau of Standards, September 27, 1985.
- Proctor, T. H., "Some Details on the NBS Conical Transducer," J. of Acoustic Emission, 1, No. 3, 173-178 (1982).

3.7.14 FOCUSED REFLECTION ACOUSTIC MICROSCOPE

Laboratory: Lawrence Livermore National Laboratory (LLNL)

Contact: Ron Streit
Lawrence Livermore National Laboratory
(415) 422-7045

The development of the Focused Reflection Acoustic Microscope (FRAM) represents a unique NDE resource at LLNL. This new ultrasonic instrumentation is unique in several important aspects including:

- ultra-broad (10:1) frequency range
- two selectable signal source options, coherent RF pulse burst or incoherent video impulse excitation
- precision imaging (color and black and white) and metrological algorithms implemented through complete digital control
- large digital storage capacity that permits near real-time replay and comparison.

The FRAM is used to investigate surfaces, layered structures and thin sheets. It is a multilens, large-frequency-range instrument that uses wide-angle, specially developed acoustic lenses with coherent pulse bursts in the 10 to 100 MHz frequency range.

The rapid and quantitative determination of acoustic attenuation and scattering losses in coated and machined surfaces of metals is important because of their direct relationship to surface mechanical properties. Because of the comparatively high scattering losses in metals and other materials of granular constituency, the useful frequency range is limited to approximately 100 MHz. The frequency dependence of measured scattering losses is a direct measure of grain size and size distribution. This information may be used to determine the elastic structural parameters that are of importance in the production of high strength materials. Direct feedback is therefore provided for the timely process control of steels and other metals with microstructure.

One early application was the characterization of steel bearing raceways that were produced by different surface treatments (machining, lapping,

etc.). The rapid and quantitative detection of surface machining and fatigue-induced cracks in both metals and ceramics is a potentially important capability for the reliable operation of sophisticated parts under stress.

It is also important to determine the machining damage and direction-dependent elastic properties in special metals due to rolling and other directional metalworking techniques. A variety of acoustic lenses with cylindrical and spherical concave depressions have become available to accommodate these special needs.

The determination of a film thickness on, or sandwiched between, solid substrate or plates is sometimes required. A specific property frequently desired in these layered structures is the strength of adhesion of the bonded layer or coating. The basic measurement performed by the FRAM, from which these parameters may be obtained, is that of Rayleigh or surface acoustic wave (SAW) velocity.

One recent application of acoustic microscopy is the detection of machining damage in beryllium. Machining damage may be determined nondestructively in the acoustic microscope via the acoustic material signature (AMS) technique. The AMS arises from interference of two active portions of the highly convergent acoustic beam, generally used in an acoustic microscope. The two portions consist of a pencil beam and a conical-shell beam. These two components recombine in the piezoelectric transducer where they are summed vectorially to produce the AMS. By using the AMS technique with the FRAM, the presence of machining-induced damage in the beryllium surface can be detected with good confidence. Although machining damage may be moderate, in situations requiring great dimensional stability such as optical and guidance systems or where fracture behavior is critical, the machining damaged layer may disrupt performance. Because this diagnostic technique is completely nondestructive and rapidly performed, it may become an important tool in the development of a high-quality, economical fabrication technique for beryllium-based structural components in the satellite and aerospace industries.

REFERENCES

- Weglein, R. D., "Development and Capabilities of the LLNL Focused-Beam Reflection Mode Acoustic Microscope," UCRL-53522 May 25, 1984 (Available from NTIS).
- Weglein, R. D., and J. E. Hanafee, "Nondestructive Detection of Rayleigh Wave Dispersion in Beryllium," February 15, 1985.
- Weglein, R. D., J. E. Hanafee and S. E. Benson, "A Nondestructive Method for Detecting Machining Damage in Beryllium," UCRL-9D9743, July 6, 1984.

3.7.15 INTERNAL TEMPERATURE PROFILE OF HOT STEEL

Laboratory: Pacific Northwest Laboratory (PNL)

Contact: Douglas K. Lemon
Nondestructive Testing Section
(509) 375-2306

DOE-sponsored work is under way to develop an in-process sensor to measure the internal temperature profile of a hot metallic form. PNL and the NBS are cooperating on this project; NBS conducts the research and PNL emphasizes the practical aspects of measuring the temperature profiles in steel billets and monitoring continuous casting operations.

The NBS research work has focused on using a laser to excite ultrasonic beams. A time-of-flight technique is used to measure the changes in ultrasonic velocity as the beams traverse the hot metallic form. Changes in ultrasonic velocity are related to changes in the travel time of the wave. The velocity changes over several different directions and paths are determined, then routed to a computational algorithm that reconstructs the internal velocity profile. The internal temperature profile is derived from this reconstruction.

PNL is investigating the NBS laser approach to exciting ultrasonic waves and is also developing electromagnetic acoustic transducers (EMATS) for the detection end of the system. NBS presently uses wave guides for momentary multiple contact with the hot metallic form. Although the PNL emphasis will be on the use of EMATS, more work is needed to develop high-temperature capability.

REFERENCES

Wadley, H. N. G., et al., "Ultrasonic Measurement of Internal Temperature Distribution." Proc. Royal Society (London), July 1985.

3.7.16 NONDESTRUCTIVE EVALUATION DEVELOPMENT FOR COMPOSITE MATERIALS

Laboratory: Argonne National Laboratory (ANL)

Contact: Ronald A. Roberts
(312) 972-5066

Ultrasonic techniques for NDE of fiber-reinforced composite materials and ultrasonic backscatter methods are being developed at ANL. Backscatter is extremely sensitive to microstructural geometry, such as fiber orientation and spacing. The relationship between composite microstructure and ultrasonic backscatter is being investigated to develop techniques to characterize composite microstructure, and to detect and evaluate anomalous conditions, such as excessive porosity and microcracking. The program emphasizes digital signal processing and correlation with theoretical models.

3.7.17 NONDESTRUCTIVE EVALUATION OF COMPOSITE LAMINATES BY LEAKY LAMB WAVES

Laboratory: Air Force Wright Aeronautical Laboratories (AFWAL)

Contact: Dale E. Chimenti
Project Engineer
(513) 255-5309

Elastic-wave propagation in fibrous composite materials has been widely investigated in recent years. However, the morphology of fiber-reinforced composites can seriously complicate the calculation of their wave propagation properties. Typically, these materials are composed of brittle, high-stiffness fibers embedded in a matrix of more ductile material that bonds the fibers together and acts as a load-transfer medium. It is clearly impractical to attempt a solution of the completely general elastic-wave problem; therefore, most prior work has employed various approximations to render the calculations tractable. AFWAL has developed an approach that offers an alternative procedure for modeling the response of composites, and gives a rational construction of the mixture momentum and constitutive-relation terms. This theory leads to simple wave propagation equations that contain the full influence of the microstructure.

Interest in the acoustic properties of these inhomogeneous and generally anisotropic materials is heightened by their increasing use in applications requiring high stiffness-to-weight ratios. Ultrasonic NDE is one useful means to insure the structural integrity of fibrous composites. To take full advantage of ultrasonic test information, a clear understanding of wave propagation characteristics in the material under examination is needed. Therefore, AFWAL has focused attention on the elucidation of plate (Lamb) waves in fluid-loaded unidirectional, fibrous composite materials, where the wave propagation direction coincides with the fiber axis. The test apparatus is shown in Figure 3.12.

Data are acquired in these experiments by exciting a broadband ultrasonic transducer with low-level rf tone bursts from a function generator. The 20 μ s bursts propagate through a water path long enough to place the sample in the

FIGURE 3.12. Experimental Geometry of Lamb-Wave Measurements in Fibrous Composite Plates (Th=Transmitter, RC=Receiver, N=Null, LW=Leaky Lamb Wave) (Chimenti and Nayfeh 1985)

transducer's far field at all frequencies. The reflected acoustic beam is detected by a second, matched transducer positioned at the same angle and distance to the sample. Data are accumulated by discretely stepping frequency and then recording the reflected signal with a broadband receiver and video detector, sampled by a gated integrating amplifier.

The results of these tests show that leaky Lamb waves constitute an effective NDE technique that is sensitive to the anisotropic nature of the composite. They can detect flaws such as delaminations, porosity, ply gaps, and variations in resin content throughout the entire thickness of the laminate. The variations observed in the mode frequencies at defect sites and the reproducibility of the data make this method an attractive alternative to attenuation measurements that can be highly variable and difficult to interpret.

REFERENCES

- Chimenti, D. E., and A. H. Nayfeh, "Leaky Lamb Waves in Fibrous Composite Laminates," 1985.
- Bas-Cohen, Y., and D. E. Chimenti, "Non-Destructive Evaluation of Composite Laminates by Leaky Lamb Waves," presented to Review of Progress in Quantitative NDE, Williamsburg, Virginia, June 23-28, 1985.

3.7.18 NONDESTRUCTIVE EVALUATION OF LAMINATED PANELS

Laboratory: Air Force Wright Aeronautical Laboratories (AFWAL)

Contact: Robert L. Crane
AFWAL/MLLP
(513) 255-5561

The detection of defects in laminated structural members has attracted considerable attention in recent years. This type of construction offers potential advantages in weight savings and in ease of fabrication and fatigue life. Researchers at AFWAL have been developing and assessing a method of edge flaw detection in laminated structures because of the greater uncertainty in predicting service life for these comparatively new types of structures.

The AFWLA method uses miniature dynamic-force transducers to detect the changes in loading history caused by the (very low level) impact of steel spheres on the transducer, which is located on the surface of the examined object. Both adhesively bonded laminates and laminated composite materials were examined. The study emphasizes flaw detection for in-service inspection instead of quality control for initial manufacture. Therefore, the project emphasizes the detection of flaws near edges of adhesively joined members where flaws associated with service occur. Stresses are greatest at the boundary and degradation from contamination such as moisture absorption initiates on the perimeter. The locality of flaws developed in-service thus reduces the effectiveness of ultrasonic inspection methods that suffer from difficulties such as edge dispersion in the vicinity of boundaries.

The test method developed at AFWAL observes the effect of a debond on the force history experienced by a small dynamic load transducer interposed between the structure of interest and a spherical striker traveling at very low velocity. The method can take advantage of structure-induced changes in the loading history itself rather than only detecting changes in the subsequent "ringing," as is done in traditional tapping inspection methods. The advantage of the present technique is in providing a quantifiable signal, several features of which provide, at least potentially, indicators of structural integrity for

laminated structures. Studies have been done on a variety of materials including aluminum, fiberglass, and graphite fabricated plates. Several variations of the piezoelectric transducer have been utilized, as well as various impact sites on the plate relative to the position of the transducer. The project has also emphasized development of a model to explain the phenomena taking place and to provide a predictive tool.

REFERENCES

Kenner, V. H., "Experimental and Theoretical Assessment of a New Technique for the Non-Destructive Evaluation of Laminated Panels," AFWAL-TR-84-4129, Ohio State University Research Foundation, February 21, 1985.

3.7.19 NONDESTRUCTIVE EVALUATION OF INTEGRALLY FABRICATED TURBINE ROTORS

Laboratory: Ames Laboratory (Ames)

Contact: R. B. Thompson
(515) 294-7803

Inspection of solid-state bonds is a problem of major importance. Pinch welds, friction welds, inertia welds, and resistance welds all play important roles in the fabrication of critical structures. A common conclusion of work in this area is that there is no universal relationship between a particular NDE parameter and bond strength.

However, in certain materials systems, various microstructural features can be changed by the bonding conditions. These microstructural changes can be detected by various nondestructive measurements and the data can be used in process control to ensure that bonding conditions are properly met. Examples include correlations between bonding conditions and the ultrasonic reflection coefficient observed in stainless steel inertia welds (B. Armstrong, et al. in press), and empirical observation of changes in the ultrasonic transmission and reflection coefficients of stainless steel pinch welds (G. H. Thomas in press; D. K. Rehbein, et al. in press) that have been found to correlate with a metallographic grading of bond quality.

With Air Force funding, Ames has undertaken a program to develop new techniques for the inspection of integrally fabricated turbine rotors focusing primarily on problems associated with the inspection of the bonds that occur when individual blades are repaired or when the entire rotor is fabricated by a bonding process. Secondary attention will be given to applying previously developed capabilities to prefabrication or postforging problems associated with monolithic rotor fabrication.

For bonded blades, the feasibility of using ultrasound to monitor the quality of the blade bonding processes will be examined, focusing on experimental assessment of the interaction of ultrasound with the bond line. Both sophisticated measurement configurations (to yield the most information) and more straightforward configurations (for easy implementation) will be surveyed experimentally.

Potential causes of poor quality bonds include contact contamination (such as a thumbprint), contamination resulting from bonding in an improper atmosphere, and microstructural changes associated with improper bonding temperatures or postbond heat treatments.

A series of measurements useful in other solid-state bonding problems will be performed on bonded samples obtained from major engine vendors. Measurements will include ultrasonic reflection and transmission coefficients, as a function of frequency; nonspecular ultrasonic scattering from the interface, including mode conversion; and harmonic generation.

These measurements will yield information on average properties of the interfaces, contaminant layers and/or metallurgically different structures, transverse variations of the microstructural changes, and microcracks or certain dislocation structures. The measurements will then be interpreted with the assistance of theoretical models presently available or developed as needed for the influence of bond line microstructure on elastic-wave propagation, combined with metallographic observation of the microstructure.

At the end of the first year, the experimental survey of the possible measurement techniques will have been completed, the most promising techniques will have been selected, and preliminary theoretical interpretations will be in hand. Future work will attempt to increase the understanding of the selected techniques for evaluating blade bonds so that they can be successfully reduced to practice.

REFERENCES

- Armstrong, B., et al., "Analysis of Inertia Welds," Review of Progress in Quantitative Nondestructive Evaluation 4, D. O. Thompson and D. E. Chimenti, eds. (Plenum Press, NY, 1985).
- Baik, J. M. and R. Bruce Thompson, "The Elastic Compliance of Imperfect Interfaces: Review and Relationship to Ultrasonic Scattering," Review of Progress in Quantitative Nondestructive Evaluation 4, D. O. Thompson and D. E. Chimenti, eds. (Plenum Press, NY, 1985), pp. 133.
- Rehbein, D. K., et al., "Immersion Ultrasonic NDE of Tubing Pinch Welds," Review of Progress in Quantitative Nondestructive Evaluation 4, D. O. Thompson and D. E. Chimenti, eds. (Plenum Press, NY, 1985).

Thomas, G. H., "Ultrasonic Nondestructive Evaluation of Tube Closure Welds,"
Review of Progress in Quantitative Nondestructive Evaluation, D. O. Thompson
and D. E. Chimenti, eds. (Plenum Press, NY, 1985).

3.7.20 NONDESTRUCTIVE SYSTEMS FOR ON-LINE MONITORING OF EROSION WEAR

Laboratory: Argonne National Laboratory (ANL)

Contact: C. Arthur Youngdahl
(312) 972-5066

Erosive wear of metallic process lines and vessels in coal conversion pilot plants has been monitored nondestructively by ANL since 1975. Recently, the problem of erosive wear in the heat exchanger piping of fluidized-bed combustion (FBC) systems fueled by coal has also been studied by ANL with the aid of nondestructive monitoring techniques. An on-line, computerized scanning system developed by ANL for surveillance of wear in the conversion plants is being adapted for use with FBCs.

Adaptation to FBCs requires modification of the ultrasonic sensing system. In the coal conversion (gasification and liquefaction) pilot plants, the erosive wear occurred on inner surfaces of process components that operated at high temperatures. Commercially available ultrasonic transducers were used for sensing and were thermally protected by specially developed acoustic waveguides attached to the outer surfaces of process lines and vessels. In FBCs the wear occurs at outer surfaces of heat exchanger piping and is to be monitored by sensors located within the piping and operating at high temperatures. Sensor designs that employ high-temperature piezoelectric acoustic elements or electromagnetic acoustic transducers are currently being tested. The multipoint location of fixed sensors, as used in conversion plants, or the use of a mobile sensor in an erosion probe are being developed at ANL.

The prior and current development and application efforts are conducted in cooperation with other institutions and industrial organizations. Industrial organizations who have cofunded development of the erosive wear system include Exxon and Gulf Oil Companies as well as several construction engineering firms at coal conversion pilot plants including the Combustion Engineering Company.

3.7.21 PHASE-INSENSITIVE TRANSDUCERS/COMPOSITE MATERIALS NONDESTRUCTIVE EVALUATION

Laboratory: NASA Langley Research Center (LaRC)

Contact: Joseph S. Heyman
Manager, NDE Research Program
(804) 865-3036

LaRC is actively investigating lightweight, high-stiffness composite materials for aerospace applications. The program includes the development of advanced matrix materials, fibers and improvements in materials processing and process control. The research program emphasizes establishing the necessary scientific base for composites NDE. Unlike metals, composites are highly anisotropic, layered, and generally have irregular structural geometries including surface roughness. Although classical NDE technologies for metals have been successfully applied to finding gross defects in composites, such as delaminations, more subtle characterization requires a new look at the physics of the propagation mechanism.

Ultrasonic transducers are piezoelectric disks packaged to optimize bandwidth or sensitivity. More recently, multilayer packaging has provided good sensitivity with broad bandwidth. Conventional transducers are phase-sensitive devices because they measure the integral of the acoustic pressure across the face of the transducer. If the acoustic field over half of the device is of different phase to the field over the remaining half, the resulting electrical output will show phase cancellation and will not represent the actual acoustic field.

With either pulse-echo or continuous-wave techniques, ultrasonic measurements on flat, parallel, and homogenous samples are straightforward; however, ultrasonic measurements made under less-than-ideal conditions, as found in modern applications, present difficulties in interpreting ultrasonic data. A significant cause of unusable data is phase modulation in the acoustic wave front due to inhomogenous samples and nonparallel reflecting interfaces. For example, phase variations due to nonparallelism make accurate absorption measurements difficult and lead to inhomogenous broadening of mechanical resonances and to modulation of pulse-echo decay patterns. Thus, there is a need for a

detection technique insensitive to phase information in the acoustic wave. One such technique, based on the acoustoelectric effect, produces a signal proportional to the incident ultrasonic flux. An ultrasonic receiver called an Acoustic-Electric Transducer (AET) has been developed at LaRC to investigate the properties of phase-insensitive detection.

The AET is a device based on phonon-charge carrier coupling in a piezoelectric semiconductor. Two fundamental relationships describe the device. First, a coupling mechanism exists between phonons and electrons that leads to absorption and dispersion of the acoustic wave by free charge carriers. Second, an electric field is generated that is proportional to the acoustic energy lost to the free charge carriers. Since the electric field is proportional to the ultrasonic phonon flux, it is independent of phase information present in the acoustic wave. This insensitivity to phase enables the AET to be used for composites.

To evaluate the properties of many composite materials, the acoustic properties must be measured as a function of frequency. In an investigation of conventional acoustic spectroscopy, some limitations became apparent. Most measurements require very short (δ function) pulses into broadband transducers. To drive much energy into a sample in such a short pulse, very high-voltage spikes are required. Most transducers are nonlinear devices at such high drives. Furthermore, the output spectra depend heavily on the shape of the drive pulse convolved with the output impedance of the driver, the cable length/capacitance, and the transducer's electrical properties themselves.

LaRC has developed a narrow-band frequency-swept measurement called Tone Burst Spectroscopy (TBS) that can develop better signal-to-noise ratios than broadband techniques. It can also utilize lower drive voltages and thus keep the transducer in its linear range.

The concept uses a spectrum analyzer coupled to a tracking synthesizer that has a center frequency equal to the frequency of the spectrum analyzer's sweeping filter. This swept tone burst concept device is especially useful for the AET transducer. The output of the transducer is stored as a function of the synthesizer's frequency, producing an accurate representation of the

acoustic attenuation of the sample under test. Together, the AET and TBS provide a tool for flaw detection characterization, determination of the acoustic properties of materials and materials properties measurement.

REFERENCES

Heyman, J. S., "Phase Insensitive Acoustic-Electric Transducer," NDE at NASA Langley June 1985, (reprint from J. Acoust. Soc. Am. 64 (1), July 1978).

3.7.22 PULSE-ECHO ACOUSTIC MICROSCOPY FOR INSPECTION OF SILICON CARBIDE COMPONENTS

Laboratory: Idaho National Engineering Laboratory (INEL)

Contacts:	D. C. Kuerth	L. A. Lott
	Principal Investigator	Technical Leader
	Materials Characterization	Materials Characterization
	(208) 526-0103	(208) 526-6436

INEL is developing a pulse-echo acoustic microscopy technique to inspect silicon carbide components as part of a program sponsored by the DOE Office of Industrial Programs to develop advanced high-temperature ceramic heat exchangers for the recovery of waste heat. The technique can be applied as a tool in lifetime prediction studies and as a means of quality control for manufacturers of ceramic materials.

The inspection technique is based on the use of specially designed high-frequency ultrasonic quartz delay line transducers with large element diameters and long focal lengths. The design of these transducers permits greater depth penetration of the acoustic wave into the high-speed ceramics while maintaining the smallest focal spot practical, thus permitting the detection of small defects. Currently, a machined surface notch 1.5 mm long, 0.05 mm wide, and 0.4 mm deep has been successfully detected and imaged through a 4.5-m-thick silicon carbide wafer.

Another unique characteristic of the inspection technique is the use of "time-of-flight" measurements to produce images. Precise measurements (2.5 ns resolution in a 5 μ s window) of the arrival times for the reflected acoustic waves are performed and the results are compared to a specified set of conditions. A deviation in time, the lack of an expected signal, or the detection of a new unspecified signal represents a defect. Color coding is used to distinguish the category of defect or the time of arrival within a specified interval. The advantage of this image production method is that fewer pieces of information are recorded in one event; therefore, imaging can be done in real time.

3.7.23 PULSED PHASE LOCKED LOOP INTERFEROMETER

Laboratory: NASA Langley Research Center (LaRC)

Contact: J. S. Heyman
Manager, NDE Research Programs
(804) 865-3036

Achieving accurate preload in threaded fasteners is an important and often critical problem throughout industry. Conventional tensioning methods that rely on torque have the disadvantage of requiring constant friction in the fastener to accurately correlate torque with preload. Because most of the applied torque typically overcomes friction rather than tensioning the fastener, small variations in friction can cause large variations in preload. An instrument called a Pulsed Phase Locked Loop Interferometer developed at LaRC measures stress as well as materials properties. When used to measure bolt preload, this system detects changes in fastener length and sound velocity, which are independent of friction. Therefore, the system is capable of accurately establishing the correct change in bolt tension. This is possible because stress, not torque, is measured. The pulsed phase locked loop (P^2L^2) system measures bolt "stretch" ultrasonically without measuring friction. With this new system, bolt preload can be measured with accuracies ranging from better than 1% for good geometry bolts to approximately 3% for fasteners having poor geometry and with measurement resolution of 1 psi.

P^2L^2 is a state-of-the-art instrument offering high resolution without the limitations of previous bolt monitors. In the P^2L^2 , continuous-wave (CW) type bolt monitors use the bolt as an ultrasonic resonator (like an organ pipe). A voltage-controlled oscillator (VCO) is gated to produce a tone burst of several cycles to derive the ultrasonic transducer. This produces an acoustic tone burst or sound wave pulse that travels down the length of the bolt and bounces off the far end. The returning echo produces an electronic signal that is received back into the P^2L^2 , is amplified and goes to a phase detector. The phase detector compares the phase of the received signal to that of the signal that went out and generates a voltage proportional to the difference in phase. When the instrument is locked, the detector changes the frequency of the VCO such that the phase of the signal out is held constant with respect to the

phase of the signal in. With this arrangement, a change in acoustic phase in the bolt causes a corresponding change in output frequency of the P^2L^2 system. Therefore, when preloading a bolt the acoustic path length changes as well as the velocity of sound; this changes the output frequency of the P^2L^2 .

By tracking the change in resonant frequency, the bolt monitor is also tracking stress (preload) changes because the change in resonant frequency is equal to a constant times the change in stress.

Use of the P^2L^2 system eliminates the need for costly alternatives, such as strain gauge bolts, and is suitable for a small portable instrument. System reliability in making accurate bolt preload measurements has been demonstrated in several critical aerospace and other field applications, in both the government and private sector. In addition to measurement of bolt preload, the P^2L^2 system has been used successfully to measure stresses in a variety of other components including wind tunnel nozzle plates. This technique has also expanded materials characterization to include measurement of higher-order (nonlinear) elastic material properties.

REFERENCES

Allison, S. G., and J. S. Heyman, "Nondestructive Ultrasonic Measurement of Bolt Preload Using the Pulsed Phase Locked Loop Interferometer," presented at 2nd Symposium on Welding, Bonding, and Fastening, NASA/LaRC, October 23-25, 1984, NDE at NASA Langley, June 1984.

3.7.24 REAL-TIME, IN SITU, NONDESTRUCTIVE MONITORING OF SOLIDIFICATION INTERFACES IN METALS

Laboratory: National Bureau of Standards (NBS)

Contact: Robert L. Parker
Center for Materials Science
(301) 921-2961

R. L. Parker is a member of the Metallurgical Processing Group, Metallurgy Division, working on the development of a monitoring system for real-time, ultrasonic metallography. The group has adapted the pulse-echo ultrasonic technique, conventionally used for flaw detection in solids, to the characterization of solidification interfaces in metals. Utilizing the acoustical impedance difference between solid and liquid phases, this new technique accurately locates the position of a solid/liquid interface in situ during solidification and melting.

In the solidification processing of metals, such as the continuous casting of steel, the position and motion of the solid/liquid interface are probably the most fundamental and significant measures of the extent of the processing. For example, in continuous casting of steel, knowing whether the solid skin thickness is sufficient to withstand the hydrostatic head of approximately 10 m of liquid steel could forestall breakouts. Breakouts, ruptures in the metal cast wall, are not uncommon but are costly and dangerous. At present, casters are run conservatively to reduce the chance of such ruptures; improved knowledge of the interface location could increase production rates and prevent breakouts. Controlling the interface velocity could also prevent or reduce chemical macrosegregation and its harmful effects on alloy performance, which result from nonuniform interface motion (Parker, Manning and Peterson 1985).

In both research and production involving solidification of metals, alloys or semiconductors, a nondestructive, in situ, real-time characterization of the solid/liquid interface would be extremely valuable. Current research on solidification of metals or alloys relies on a postmortem autopsy to determine the location, orientation or structure of the interface. This is accomplished by chilling or quenching the partially molten specimen, then cutting and polishing

it for reflection optical microscopy. It would be much more convenient and useful to know what occurs during solidification in real time.

Ultrasonic flaw detectors generate a short pulse of ultrasound, using an electrical pulse fed into a piezoelectric transducer. The ultrasound, generally in the frequency range of 1 to 10 MHz, is then directed into the material to be tested. Echoes resulting from reflection of the sound pulses from defects return to the sending transducer, which then acts as a receiver, converting the echoes into electrical pulses. Appropriate circuitry displays both the original pulse and the echoes on an oscilloscope screen, where the time, and consequently the distance between original pulse and echo, can be determined.

The solid/liquid interface in a melting or freezing metal can also be detected because of the measurable difference in both sound velocity and density across the interface. In a typical case, the velocity of sound is about 10% less in the liquid than in the solid; density is about 3 to 5% less in the liquid. These provide an acoustic impedance mismatch of typically 13 to 15%. In the case of tin, about 10.8% of the pressure amplitude of the incident wave is reflected (about 1% of the ultrasonic energy). Although this is small compared to the nearly 100% reflected energy from a planar crack or void, the receiver gain of modern pulse-echo equipment can cover a range of 80 decibels or more, so that the signal can be detected.

The group has presented experimental results for pulse-echo observation of the melting and freezing of pure iron, 304 stainless steel, and tin using Bridgman-type furnaces with unidirectional heat flow, at frequencies from 1 to 5 MHz. For both iron and steel, rapid grain growth in the solid phase at high temperatures can strongly attenuate the sound waves and can also produce back-scattered waves that obscure the identification of the solid/liquid echo. In alloys the presence of a "mushy zone" rather than a sharp interface further reduces the reflected signal. These signal/noise problems were successfully overcome by a transducer spatial-scanning technique with computer signal averaging that permits the interface to be located even in concentrated alloys.

Work continues on signal-processing development, especially for such sensors as EMAT transducers. These transducers have less sensitivity than

PZT transducers but are better suited to on-line process monitoring applications (Parker and Manning 1984). A primary objective is to provide techniques for process control in the continuous casting of steel and to provide a monitoring method to prevent breakouts. Breakouts may happen approximately 6 times per year per machine and cost from \$100,000 to \$200,000 per occurrence.

REFERENCES

- Parker, R. L., J. R. Manning and N. C. Peterson, "Application of Pulse-Echo Ultrasonics to Locate the Solid/Liquid Interface During Solidification and Melting of Steel and Other Metals," J. Appl. Phys. 58 (11) December 1985, 4150 - 4164.
- Parker, R. L., and J. R. Manning, "Ultrasonic Measurement of Solid/Liquid Interfaces Position During Solidification and Melting of Metals." NBS Technical Activities 1984, 64-65.

3.7.25 SPECIAL LOW-FREQUENCY TRANSDUCERS FOR CONCRETE INSPECTION

Laboratory: Argonne National Laboratory (ANL)

Contact: Karl J. Reimann
(312) 972-5066

Inspection of concrete structures with ultrasound imposes specific requirements on the transducer. To penetrate through the required thickness of concrete, a very low frequency (<100 kHz) is preferred. Reduction of beam spreading requires a large transducer at low frequencies. These considerations led to the design and construction of a low-frequency (180-Hz), 10 in. x 10 in. ultrasonic transducer. The active element of the piezoelectric transducer consists of epoxied layers of polyvinylidene fluoride (PVDF), 7- μ m-thick sheets with interspaced aluminum electrodes. Preliminary tests were conducted on 12- and 18-in.-thick refractory and Portland cement (PC) concrete blocks using the PVDF transducer in a pulse-echo mode. Multiple backwall echoes were obtained in the refractory concrete and a single echo in the PC concrete.

Work is in progress to establish the performance of PVDF transducers in the following areas:

1. significant concrete variables
 - a. thickness (attenuation)
 - b. aggregate size
 - c. internal delaminations (such as synthesized cracks with a rough surface)
2. transducer operating variables
 - a. input electrical power needed and allowed
 - b. pulse-echo operation versus receiver operation
 - c. electronic signal processing required to enable transducers to be used effectively.

Objectives of future work include the evaluation of a PVDF transducer in under-water testing of concrete structures and remote transducer manipulation during such tests.

3.7.26 STANDARDS FOR ULTRASONIC MEASUREMENT OF RESIDUAL STRESS

Laboratory: National Bureau of Standards (NBS)

Contact: Donald Eitzen or G.V. Blessing
Center for Manufacturing Engineering
(301) 921-3646

A residual stress material standard for ultrasonic and other NDE measurements is being developed. Residual stress, also known as internal stress, is the stress system within a solid that is not dependent on external forces. A reliable nondestructive method to evaluate the residual stress state of an object is of much interest to materials scientists, design engineers, and safety officials (Blessing, Hsu and Proctor 1984b).

Shrink-fit, ring-plug specimens fabricated with known levels of residual stress show promise for an ultrasonic measurement standard. An aluminum ring-plug sample has recently been tested. A stressed state was produced by shrink-fitting an aluminum alloy plug and ring (see Figure 3.13). Ultrasonic shearwave, time-of-flight measurement scans were made across the sample diameters. Similar measurements were made on a nonstressed sample. The experimental results were in good qualitative agreement with acousto-elasticity theory (Blessing, Hsu and Proctor 1984b).

In addition to ultrasonic measurements that have focused on relative stress levels in the ring-plug sample, strain measurements using a neutron diffraction technique have been taken. They corroborate the absolute stress state of the sample calculated from material modulus and physical parameters. An independent research team at Stanford University has also evaluated the stressed aluminum sample ultrasonically, and their results agree with both longitudinal and shear-wave measurements at NBS (Blessing, Hsu and Proctor 1984a).

Future work may involve the fabrication and evaluation of ring-plug samples made of other materials, including steel. NBS is planning to provide samples with known residual stress as Standard Reference Materials. This work has clearly advanced the use of ultrasonic velocity measurements in measuring residual stress accurately and reliably.

FIGURE 3.13. Sample Geometry of Ring-Plug Configuration and Residual-Stress Profile for the Principal Stress Difference According Elasticity Theory (Blessing, Hsu and Proctor 1984b)

REFERENCES

- Blessing, G. V., N. W. Hsu and T. M. Proctor, "Ultrasonic Residual Stress Measurements," NBS Tech. Activities 1984, p. 69, (1984a).
- Blessing, G. V., N. N. Hsu and T. M. Proctor, "Ultrasonic Shear-Wave Measurement of Known Residual Stress in Aluminum," Exp. Mechanics 24:218-221 (1984b).
- Prask, H. J., and C. S. Choi, "NDE of Residual Stress in Uranium by Means of Neutron Diffraction," J. Nuclear Materials 126:124-131 (1984).

3.7.27 STRESS LEVEL MEASUREMENT IN RAIL CAR WHEELS

Laboratory: NASA Langley Research Center (LaRC)

Contact: Joseph S. Heyman
Manager, NDE Research Programs
(804) 865-3036

Monitoring of the stress level in rail car wheels is important because safe operation requires that the residual stresses (hoop) in the wheel be in the compressive mode so that the wheel will handle applied stresses and not be subject to cracking or spalling. The stresses placed in the wheel, as a result of manufacturing and heat treatment, can be reduced or removed by the application of braking, which causes thermal cycling and stress relief. Through the use of the magnetoacoustic/pulsed phased locked loop (P^2L^2) technique, it is possible to determine if the 1045 steel in railroad wheel material is in compression, neutral, or tensile-stress condition. The technique appears to be sensitive to the percentage of carbon in the steel alloy; 1045 steel provides a response that is ideal for this application. Higher and lower carbon content alloys offer a slightly different and lesser response, making them less amenable to study by this means.

Rail wheels operate in compression. If the braking or heating anneals out residual compressive stress, natural velocity curves will be shown and provide a basis for removing the wheel from service. A magnetic approach that has proven quite successful in studying stress in ferrous materials involves use of low field magnetic domain wall effects on the acoustic natural velocity of the material.

The physical model of this approach is that the unit cell in the ferrous structure is asymmetrical with respect to the magnetic domain. Therefore, stress induces domain alignment: mainly 180° walls parallel to the tensile stress axis (with net zero magnetization) and 180° walls perpendicular to the compressive stress axis. The application of an external magnetic field favors growth of domain in its own direction. The growth or removal of 90° walls with an external field results in a dimensional change in the solid and a corresponding change in the natural velocity. The change in natural velocity with

magnetization depends on the initial state of stress, and is the basis for this measurement. The use of the magnetic field is essential because it allows the type or sign of stress to be identified, eliminating the need for standards. The magnetic field aligns the magnetic poles, which causes a change in the length of the material. When exposed to a magnetic field, compressive stress causes a reduction in the natural velocity. The high resolution of the P^2L^2 permits measurement of the small natural velocity changes on the order of parts in 10^7 that accompany the low magnetic fields. This is necessary to determine the effects of stress.

The P^2L^2 measures small changes in acoustic propagation time. A change in propagation time is proportional to a material strain and an ultrasonic velocity change. Because of inaccuracies inherently associated with measuring in the time domain, the P^2L^2 system was developed to measure in the frequency domain where stress-induced acoustic phase shifts can be measured precisely. The acoustic phase is a function of acoustic frequency and propagation time; the derivative of the phase with respect to stress is a function of the stress-induced changes of propagation time and frequency. Since the P^2L^2 system maintains constant phase, the stress derivative of the acoustic phase is forced to equal zero. Thus, the stress-induced frequency shift measured by the P^2L^2 is directly related to the small stress-induced change in ultrasonic pulse propagation time. Therefore, the stress-induced frequency shift is proportional to a stress-induced strain and a stress-induced velocity change.

The ability to determine the effects of stress can also be applied to railroad track to assure that kinking out, due to local restraint of thermally induced (solar heating) rail elongation, has not deformed plastically and weakened the rail thus making a derailment possible. This work is being funded by the Federal Rail Administration and the Department of Transportation.

This tool/knowledge can also be applied to pressure vessel inspection and bridge inspection.

REFERENCES

- Allison, S. G., and J. S. Heyman, "Non-Destructive Ultrasonic Measurement of Bolt Preload Using the Pulsed Phased Locked Loop Interferometer," presented at 2nd Symposium on Welding, Bonding and Fastening, NASA LaRC, October 23-25, 1984, NDE at NASA Langley, June 1985.
- Heyman, J. S., "Advanced NDE Technology for Material Characterization," presented at DOD 1984 MTAG Test and Inspection Mini-Symposium, November 25-29, 1984, NDE at NASA Langley, June 1985.

3.7.28 SYNTHETIC APERTURE FOCUSING TECHNIQUE (SAFT) FOR ULTRASONIC IMAGING

Laboratory: Pacific Northwest Laboratory (PNL)

Contact: Steven R. Doctor
Nondestructive Testing Section
(509) 375-2495

A major area of NDT involves defect characterization. Flaws or defects must be detected and classified by their size, shape, orientation, location, and composition to fully evaluate the safety and performance of structural and functional components. PNL researchers are advancing an ultrasonic imaging technique that automates defect characterization in piping, pressure vessel, and heavy section material.

Called the Synthetic Aperture Focusing Technique for Ultrasonic Testing (SAFT-UT), this imaging method can be adapted to many different types of materials, specimen geometries, and ultrasonic propagation modes. Such flexibility makes SAFT-UT an imaging technique well-suited to industrial applications (Busse, Collins and Doctor 1984). In addition, the components are generally commercially available, making the technique practical for industrial use.

"Synthetic Aperture Focusing" refers to a process in which the focal properties of a large-aperture, focused transducer (lens, antenna, etc.) are mimicked or synthesized from a series of measurements made using a small-aperture transducer scanning over a large area. Various processing methods are used to focus this collection of data, including beamforming, coherent summation, and synthetic aperture processing techniques. Synthetic aperture focusing has several advantages over physical focusing techniques: SAFT-US has more flexibility on data collection and image formation and can inspect test objects of irregular size and shape. Physical-focus imaging requires transducers with different focal properties designed for every different part to be inspected (Busse, Collins and Doctor 1984).

SAFT-imaging is performed by illuminating the given area of interest with a divergent sound beam; the radio frequency (RF) data returned from internal echoes in the material are then digitized. A transducer scans the material in rectilinear fashion to obtain a matrix of data. This RF data is synthetically

focused and processed using a signal-processing algorithm and a high-speed minicomputer. The algorithm allows each point within the inspected volume to be imaged at maximum available resolution. The images are therefore volumetric; they provide a three-dimensional map of any defect and the surrounding area (Busse, Collins and Doctor 1984).

The first digital implementation of a one-dimensional SAFT processing system was demonstrated in the area of NDT by the University of Michigan in 1976; SAFT medical imaging was first demonstrated in 1975 at the Mayo Clinic. The need for high-speed data collection in medical imaging has subsequently caused the SAFT approach to be abandoned for medical applications. In NDT, however, the goals of high resolution and imaging system flexibility have far outweighed data acquisition speed requirements. Research activity in this area has been quite brisk. Many important developments have come from the University of Michigan and the University of Missouri at Columbia. Preliminary work on field validation of SAFT systems was done by Southwest Research Institute (SWRI) (Busse, Collins and Doctor 1984).

PNL's research and development efforts are centered on the development of a field-worthy SAFT-UT nondestructive inspection system. One goal of this work, sponsored by the NRC, is to develop and implement a real-time, high-resolution SAFT-UT system to detect and quantify the extent of defects and cracks in nuclear reactor critical components (pressure vessels, primary piping systems, and nozzles) (Busse, Collins and Doctor 1984).

Materials studied include carbon steel, stainless steel, cast stainless steel, and aluminum. Good characterization has been achieved of defects in materials with thicknesses from 0.5 to 12 in. The PNL SAFT system uses both a UT pulse-echo approach and a two-transducer tandem approach for improved defect characterization.

Technology transfer is under way. Combustion Engineering (Windsor, CT and Chattanooga, TN) is working closely with PNL to use and verify the SAFT-UT technique. They plan to eventually offer the SAFT equipment as a commercial system.

REFERENCES

"Ultrasonic Imaging - Full Volume Characterization," PNL Research Results Information Sheet, n.d.

Busse, L. J., H. D. Collins and S. R. Doctor, "Review and Discussion of the Development of Synthetic Aperture Focusing Technique for Ultrasonic Testing (SAFT-UT)," Report NUREG CR-3625 (PNL-4957), March 1984.

3.7.29 ULTRASONIC AND ACOUSTIC EMISSION TRANSDUCER DEVELOPMENTS

Laboratory: National Bureau of Standards (NBS)

Contact: Donald G. Eitzen or Thomas M. Proctor
Center for Manufacturing Engineering
(301) 921-3646

NBS provides calibration services for ultrasonic and AE transducers, and is active in the design, construction, and testing of new transducer standards. The recently developed NBS conical transducer has been successfully tested and is currently available for purchase from the NBS Office of Standard Reference Materials (SRM No. 1856) (Proctor, Greenspan and Eitzen 1983).

The NBS conical transducer measures dynamic surface displacement in the normal direction; a tangential displacement transducer is being developed as a companion standard. Both the normal and the tangential components of motion must be measured to fully describe the dynamic displacement at a point on a surface. Dynamic displacement transducers are needed as transfer standards for the secondary calibration of AE sensors, as tools in the development of signal processing techniques for AE source characterization, and as transducers for field applications (Proctor, Greenspan and Eitzen 1983).

The NBS conical transducer measures the normal component of surface displacement with a sensitivity of 10^{-13} m. The tangential transducer has gone through several versions; the latest one has very good fidelity. Newly developed fabrication techniques have minimized the problem of cross sensitivity to normal displacements, a problem with earlier versions.

Transducers are extremely useful devices that convert physical quantities, such as temperature or dynamic displacement, into a voltage or some other electrical quantity. These signals can then be manipulated by electronic circuits, quantified by analog-to-digital converters, and logged and analyzed by computers. The results of these physical measurements can be used to control manufacturing processes, with on-line control provided by a dedicated computer or microprocessor.

Transducers are usually designed as special-purpose units with specific fundamental frequencies. NBS researchers have developed a new general-purpose

ultrasonic transducer that has a multifrequency operational capability. This "universal" transfer standard transducer could replace many older units, suitable only for single-frequency operation (Fick et al. 1984).

Lithium niobate is the piezoelectric crystal element used in this new transducer. Lithium niobate requires only 5% of the electronic drive voltage for any given output, compared with the more conventional quartz transducer element used in earlier transfer standards. Lithium niobate also allows a lower fundamental resonance (0.5 MHz), which in turn allows overtone operation at convenient 1 MHz step intervals. The upper frequency limit of this unit was found to be 78 MHz in some tests (Fick et al 1984). The usable range will probably lie between 5.5 MHz and 25 MHz. Units now available to the public can be calibrated at output powers of 5 to 500 mW at frequencies between 1 MHz and 20 MHz (SRM No. 1855).⁽³⁾

REFERENCES

- Fick, S. E., et al. "An Absolute Power Transfer Standard." NBS Journal of Research, 89:(2)209-212, March-April 1984.
- Proctor, T. M., "Acoustic Emission Transducer Developments." NBS Technical Activities 1984, 76-77.
- Proctor, T. M., F. R. Breckenridge and Y. H. Pao, "Transient Waves in an Elastic Plate: Theory and Experiment Compared." J. Acoust Soc. Am. 74 (6) December 1983, 1905-1907.
- Proctor, T. M., M. Greenspan and O. G. Eitzen, "Dynamic Displacement Transducers for Acoustic Emission." NBS Technical Activities 1983.

3.7.30 ULTRASONIC CHARACTERIZATION OF POROSITY IN CAST ALUMINUM

Laboratory: Ames Laboratory (Ames)

Contact: James H. Rose
(515) 294-8152

This effort conducted by Ames Laboratory for the Air Force entails the theoretical development of a method for characterizing porosity in cast aluminum using frequency-dependent ultrasonic attenuation. It is related to similar Air Force-sponsored work (managed by Ames) at Ohio State University. This work involves experimental examinations using ultrasound to measure volume fraction and size of pores in A357 cast aluminum alloy. Both theoretical work and experiments on laboratory samples have established a firm basis for the technique.

Work under way at Ames addresses several questions affecting the reliability of the method in inspection situations including: 1) effects of rough and "as cast" surfaces on the inference of the attenuation from the measurements, 2) the interpretation of the attenuation when the pores are nonspherical (as they are in microshrinkage porosity), 3) the effects of multiple scattering on the inference of the attenuation, and 4) the inference of the attenuation from the reflected signal for special part geometries.

Work at Ohio State University comprises: 1) sample production using sand casting, particularly samples with a majority of microshrinkage; 2) ultrasonic characterization examining the effects of the as-cast surface, the porosity gradient in the cast as a function of mold geometry, shear wave velocity as a secondary means of characterizing porosity and the effect of hot isostatic processing (HIP) on the frequency response of attenuation and on the curing of defects; 3) scanning electron microscopy analysis of HIP samples; and 4) interaction of theoretical considerations.

3.7.31 ULTRASONIC EVALUATION OF CERAMIC AND RAPIDLY SOLIDIFIED ALLOY MATERIAL AND JOINTS

Laboratory: Idaho National Engineering Laboratory (INEL)

Contact:	L. A. Lott	K. L. Telschow
	Technical Leader	Principal Investigator
	Materials Characterization	Materials Characterization
	(208) 526-6436	(208) 526-1264

This project is part of the Strategic and Critical Materials program at the INEL sponsored by the Bureau of Mines and administered through the DOE. The overall goal of this program is to provide fundamental knowledge to the scientific community so that superior mineral production processes can be developed and substitutes for various strategic materials can be perfected. This NDE task is part of the Conservation/Substitution branch of the program that focuses on perfecting the technologies for utilizing Rapidly Solidified Alloys (RSAs) and high-performance ceramics. These advanced materials depend on specific microstructural features for the special properties that permit their use as substitutes for strategic materials. To assure the presence of these specific microstructural features and to determine the material's fitness for purpose, the traditional role of NDE must be expanded from the usual task of determining crack size and shape to include a basic understanding of the interaction between probing radiation (ultrasound, x-rays, etc.) and the material microstructure. From this basic understanding, methods can be developed to nondestructively measure and characterize material grain size, microvoids, inclusions, precipitates, porosity and density variations in ceramics and RSAs.

Current research focuses on the application of very high-frequency ultrasonic measurements for the evaluation of material homogeneity, anisotropy, and grain size. The exceptionally small grain and microvoid sizes found in RSAs and ceramics demand that ultrasonic frequencies in the range of 30 to 100 MHz be used and new techniques be developed for effective application. Primary emphasis is placed on determining microstructural features from backscattered radiation. This technique is preferred because it requires access to only one side of the material under investigation, which lends itself well to field adaptability. Joints between these materials are being investigated by various

forms of acoustical microscopy to evaluate joint size, spatial homogeneity, and bond quality. Emphasis is placed on method development, theoretical prediction, and experimental verification.

REFERENCES

"Strategic and Critical Materials Annual Report, May 1985," Bureau of Mines, Department of the Interior, Contract J0134035, Idaho National Engineering Laboratory, Department of Energy, Idaho Falls, ID 83415.

3.7.32 ULTRASONIC EVALUATION OF MATERIAL PROPERTIES

Laboratory: NASA Lewis Research Center (LeRC)

Contact: Alex Vary
(216) 433-6019

Ultrasonic NDE techniques are commonly used to measure the microstructural variations, associated extrinsic properties, and diffuse flaw populations of structural materials. Specification of flaw criticality and prediction of structural reliability depend on knowing these mechanical properties and morphological conditions. The speed of wave propagation and wave energy loss are the basis of ultrasonic mechanical property determinations. They are determined by measuring physical and acoustical properties via the interaction of elastic stress waves with microstructural and morphological factors.

Although significant empirical correlations exist between ultrasonic measurements and mechanical properties, they often appear fortuitous or accidental. The fundamental relations underlying many of the correlations are currently unknown. Research at LeRC has involved work with three conceptual models to advance the theoretical bases for ultrasonic materials assessment.

The empirical approach to correlating ultrasonic quantities and mechanical properties is epitomized by the "adaptive learning network" (ALN) method. The ALN method requires no fundamental understanding of the interrelations between ultrasonic measurements and the mechanical properties evaluated. The method relies on collecting sufficient ultrasonic data and then applying multiple regression analysis procedures. Although the ALN method works, the fundamental interrelations remain unknown.

Researchers at LeRC concentrated on the study of fracture toughness of polycrystalline solids to link ultrasonic quantities with mechanical properties. Fracture toughness is a measure of a materials resistance to catastrophic crack propagation. Spontaneous stress waves that arise during microcrack nucleation and fracture are ultrasonic in nature. It is reasonable to expect, therefore, that ultrasonic probing will show the effect of the microstructure on the stress waves caused by fractures and similar processes.

Three conceptual models have been formulated by LeRC researchers to help establish a basis for interrelating ultrasonic, microstructural and mechanical property factors: the stress wave interaction (SWI) model, the microstructure transfer function (MTF) model, and the microcrack nucleation mechanics (MNM) model.

The SWI model proposes that spontaneous ultrasonic stress waves interact with material microstructural factors to promote microcracking and catastrophic crack extension. The SWI model states that critical sites are activated by stress waves emitted at the onset of catastrophic crack growth. These critical sites are potential microcrack nucleation sites that can absorb or release stress wave energy. The model assumes that an avalanche effect occurs in which increasing numbers of crack nucleations sites are activated by the advancing stress wavefront. Moreover, the advancing stress wavefront is assumed to be reinforced as energy is released at the nucleation sites.

The MTF model considers material micro-structures as mechanical "filters" that have a transfer function definable in terms of ultrasonic attenuation coefficients. The MTF model is a link between the SWI model and the MNM model that describes the mode of stress wave interaction with the crack nucleation sites.

The MNM model describes how the "critical microcrack nucleation sites" described by the SWI model interact with one another. The model states that when one site releases energy by fracturing, the energy is carried by the stress wave to an adjacent site. Given an existing static stress field around the second site, it is only necessary for the impinging stress wave to impart enough energy to take it above a fracture threshold. The energy imparted to this second site depends on the ultrasonic attenuating properties of the micro-structure between the two sites.

These theories and other ultrasonic theories are studied through the use of two particular ultrasonic techniques. The first, the pulse-echo method, uses a single probe as both the sending and receiving transducer. Coupling a transducer to a material sample produces a series of ultrasonic echoes that can be analyzed either in the time or frequency domain. The second method, known as the acoustic-ultrasonic method, uses two transducers, one to send signals

and the other to receive. The object of the acoustic-ultrasonic method is to generate elastic waves that will interact with material morphology and boundary surfaces in a manner similar to the spontaneous stress waves that arise at the onset of microcrack nucleation, fracture, etc. The acoustic-ultrasonic waveform carries information about the material through which it passes. It is a function of velocities, attenuations, dispersions, multiple reflections, etc. Experiments have shown that the acoustic-ultrasonic waveform will yield significant correlations with mechanical properties.

REFERENCES

Vary, A., "Ultrasonic Nondestructive Evaluation Microstructure and Mechanical Property Interrelations," NASA Technical Memorandum 86876, October 1984.

3.7.33 ULTRASONIC HIGH-SPEED DATA ACQUISITION SYSTEM (ECHO TRAP III)

Laboratory: Sandia National Laboratories (SNL-A)

Contact: William Shurtleff
(505) 844-3500

The Echo Trap III, a third-generation computer interface, links standard ultrasonic pulse-echo/through transmission units with minicomputer systems. Maximum utilization of ultrasonic pulse-echo testing techniques requires fully automated scanning systems. To use a system of this type efficiently, it is first necessary to electronically preprocess the basic ultrasonic signals to put the information into a suitable form for computer data recording and analysis. The Echo Trap III performs this function and improves on first- and second-generation instruments.

The basic ultrasonic pulse-echo signal is generated in the following way. An ultrasonic transducer (usually a piezoelectric device) is first stimulated by an electronic signal or pulse. This causes the transducer to emit ultrasonic waves in the form of short bursts of ultrasonic energy at the resonant frequency of the transducer. These waves are then propagated through the material being tested and any anomalies or flaws encountered will reflect a percentage of the energy in the wave. This reflected energy (or echo) propagates back through the material and is received, usually by the same transducer that generated the initial wave. The sum of the time it takes for the wave to travel to an anomaly plus the time it takes the echo to return is a function of the depth of the anomaly in the material. The amplitude of the received echo is a function of the severity of the anomaly. These are the two most important parameters of the echo signal.

Because the third-generation interface is almost completely digital, it has some special requirements. First, the number of flaws that may be detected with any one transducer stimulation pulse is normally quite low. Because each flaw can be considered as a mask to any additional flaws that lie beneath it, each successively deeper flaw requires a separate channel for analysis and recording. If the number of channels is a whole integer power of two, the

output multiplexing process is simple using a binary counter to address the channels. Consequently, four flaw channels are used in Echo Trap III and have been found to be quite adequate.

It was initially postulated that high-echo amplitude resolution would be required, but experience with the second-generation interfaces has shown otherwise. Small geometric variations from test to test make it very difficult to ensure amplitude accuracy of better than a few percent. Also, because of the extremely short duration of some of the echoes (less than 50 ns), a very high-speed A/D converter would be necessary to digitize the signal. Because resolution and speed are basically opposing parameters of an A/D converter, some compromise was necessary. A special 4-bit binary A/D converter was built. Although this allows only 15 flaw amplitude levels, it has proven to be very satisfactory.

To make reasonably accurate sound velocity measurements and to locate flaws accurately, time resolution was desired on the order of 0.1% full scale. Therefore, 10-bit binary counters were used in Echo Trap III. Although greater resolution is easily obtained, the accuracy of these readings could be questioned. This is because the echo time gates are determined by the echo signals themselves as they exceed the threshold level. The threshold is an operator variable and the echo signal rise time is a function of the specific test; therefore, the actual elapsed time to each echo is difficult to define.

To maintain maximum bit resolution over a broad range of delay times, a time base selector is provided. This allows operation from 25 nsec full scale to 400 nsec full scale in appropriate steps.

The technology demonstrated by the Echo Trap III, if upgraded to current electronics, could find industrial applications.

REFERENCES

Stoker, G. C., "A Third Generation Computer Interface for Ultrasonic Pulse Echo Nondestructive Testing," SAND 75-0056, February 1975.

3.7.34 ULTRASONIC INSPECTION OF MATERIAL MICROSTRUCTURE

Laboratory: NASA Lewis Research Center (LeRC)

Contact: Edward R. Generazio
(216) 433-6019

LeRC researchers are studying the effects of polycrystalline solids on ultrasonic signals. They are particularly interested in relating the observed attenuation of ultrasonic signals to the mean grain diameter of the solid under observation. Although experimental and theoretical results agree for some polycrystalline materials, many are so complex that they are not adequately described by existing theory. Because structural materials generally exhibit complex microstructures, the development of methods to verify microstructures is of great interest.

LeRC research uses ultrasound to verify the effects of heat treatment on polycrystalline samples of nickel and copper. The study concentrated only on the attenuating effects due to the mean grain size of the solid. No attempts were made to determine the mode of scatter attenuation (Rayleigh, stochastic, etc.) that was dominant for a particular experimental trial. Attenuation as a function of frequency was determined for a sample having a known mean grain diameter. Then this function could be scaled to determine the mean grain size of other samples of the same material with different mean grain diameters. The results of this study suggest an ultrasonic, nondestructive approach for verifying heat treatment of metals.

REFERENCES

Generazio, E. R., "Ultrasonic Verification of Microstructural Changes Due to Heat Treatment," reprint from CP-2383, "Analytical Ultrasonics in Materials Research and Testing," conference held at NASA Lewis Research Center, Cleveland, Ohio, November 13-14, 1984.

3.7.35 ULTRASONIC INSPECTION RESEARCH AND DEVELOPMENT

Laboratory: Oak Ridge National Laboratory (ORNL)

Contact: W. A. Simpson, Jr. or R. W. McClung
Nondestructive Testing Group
(615) 574-4839

Ultrasonic inspection R&D at ORNL ranges from applications development to signal processing, emphasizing ultrasonic spectroscopy, time deconvolution, and other techniques for quantitative flaw characterization.

Current and recent activities involving ultrasonics include:

- research for anisotropic materials (e.g., stainless steel welds)
- signal processing techniques for quantitative flaw characterization
- characterization of materials and flaws in metals, graphite, composites, and ceramics
- in-service inspection techniques for steam generators and piping welds
- techniques for thin sections for encapsulation of isotopes and superconductor cables
- technology for thick-section steels for pressure vessels
- measurement of elastic properties
- high-resolution techniques for miniature thermo-electric devices for space satellites
- standardization activities through ASME and ASTM.

An example of recent ultrasonic work is the effort to characterize flaws in stainless steel welds. Two theoretical models for scattering of ultrasound from these flaws were developed, and equipment was assembled to conduct experimental studies and to confirm theoretical development. One model was based on an elastodynamic analog of a geometrical optics approach and one on the boundary-value solution of scattering from spheres in elastic media.

REFERENCES

- Cook, K. V., R. A. Cunningham and W. A. Simpson, Jr., "Ultrasonic Techniques for Bore-Side Inspection of Tube-to-Tube Sheet Welds."
- Simpson, W. A., Jr., and R. W. McClung, "Ultrasonic Characterization of Advanced Composite Flywheels," ORNL/TM-9046, August 1984.
- Simpson, W. A., Jr., et al., "Ultrasonic Flaw Characterization for Stainless Steel Welds," ORNL-6175, January 1986.

3.7.36 ULTRASONIC MEASUREMENT OF SURFACE ROUGHNESS

Laboratory: National Bureau of Standards (NBS)

Contact: Gerald V. Blessing
Center for Manufacturing Engineering
(301) 921-3646

Surface roughness has long been recognized as a parameter affecting the ultrasonic echo amplitude in a material specimen; however, little work has been done to systematically study the effect of different machined roughnesses on the transmissivity and reflectivity of ultrasonic waves (Blessing, Bagley and James 1984). Working in association with ASTM Standards Committee E.7, G. V. Blessing began investigating the influence of surface roughness on ultrasonic attenuation in steel. These investigations showed that ultrasonics had potential for measuring surface roughness in manufacturing and field environments.

The ASTM test scenario called for the relative amplitude measurement as a function of frequency of successive back-wall echoes in a series of one-side roughness specimens. A water delay line pulse-echo technique was used in all such tests, in one case with the specimen back surface immersed, and in the other with it dry (air backing). Measurements were made first with the rough side facing the transducer, and then repeated with the smooth side facing the transducer. A set of steel specimen disks were fabricated with surface roughness ranging from a relatively smooth, ground surface to a very rough one. (Surface features were comparable to the ultrasonic wavelength).

The samples were fabricated from M50 (high-speed tool) steel in the shape of disks of approximately 10 cm in diameter and 1.9 cm in thickness. All samples had a smooth, ground finish on their back surface. The roughness of the front surfaces differed considerably. Of the seven samples, four had their roughness machined by a shaper, one by grinding (same as the four back surfaces), one by bead blasting, and one by grit blasting. The machining technique for the four shaped samples resulted in two-dimensional (parallel-grooved) roughness surfaces, and a periodicity approximately proportional to their roughness values. A sample cross-section, perpendicular to the lay, would reveal a profile of triangular peaks and cusped valleys.

A pulse-echo multicycle tone burst technique was used to drive a set of quartz transducers at their respective resonance frequencies in the range of 1 to 20 MHz. The transducers used with water immersion were single-crystal X-cut quartz elements, lightly dampened with a polyethylene backing sheet for support. Six separate transducers were used, operating at their respective fundamental frequencies of 1.0, 2.25, 5.0, 10.0, 15.0, and 20.0 MHz. Figure 3.14 illustrates the arrangement of the transducer relative to the sample.

The transducer used for airborne ultrasound was a 2.5-m-diameter lead-zirconate-titanate ceramic transducer, driven with a single-cycle tuned radio frequency signal at 2.3 MHz. An air gap of 1.0 cm separated the transducer and sample.

Over the range of available surface roughnesses (1 to 23 μm rms in height), an apparent increase in ultrasonic attenuation as a function of roughness was observed in steel at the higher frequencies studied--from 10 to 20 MHz. No such effect was observed at the lower frequencies studied--from

FIGURE 3.14. Experimental Configuration of a Transducer Operating as Both a Transmitter and Receiver, Relative to a Steel Sample for Successive Echo Amplitude Measurements (Blessing, Bagley and James 1984)

1 to 5 MHz. Front surface reflectivity measurements as a function of roughness yielded the same results whether using airborne or water-immersed ultrasound of an equivalent wavelength for that medium.

Researchers believe the practical application of airborne ultrasound techniques should not be overlooked for contactless NDE of surface features such as roughness, scratches, and dents in addition to surface proximity, and orientation.

An ultrasonic measurement system is being developed that would monitor surface roughness during machining processes. The system would measure surface roughness in the nominal range of 1 to 25 μm , and would also measure part thickness or diameter to an accuracy of about 25 μm .

Work has progressed through the development of a laboratory system for sensing tool condition by in-process monitoring of part surface finish. The method uses pulsed ultrasound to sense the part roughness. The ultrasound travels down the coolant stream and interacts with the part surface. Some of ultrasound is reflected, travels back up the coolant stream and is measured by an ultrasonic sender/receiver located in a specially designed coolant nozzle. The measure of the amount of ultrasound returning up the coolant stream is a measure of part roughness. For the very high frequencies presently being used (5 MHz) a range of finishes from 1 to 25 μm can be covered. Differences of finish of less than 3 μm can easily be detected; scratches or gouges can also easily be detected.

The first results were obtained on flat stationary specimens using water. More recently the technique has been demonstrated to work on round rotating parts at speeds greater than 1000 sfpm with typical water-based machine tool coolants using a laboratory set up. The next steps will be to construct a shop floor prototype system and install it on the turning work station of NBS's Automated Manufacturing Research Facility.

REFERENCES

Blessing, G. V., P. P. Bagley and J. E. James, "The Effect of Surface Roughness of Ultrasonic Echo Amplitude in Steel," Materials Evaluation (1984).

3.7.37 ULTRASONIC TESTING OF PLATES CONTAINING EDGE CRACKS

Laboratory: NASA Lewis Research Center (LeRC)

Contact: Alex Vary
(216) 433-6019

Conventional ultrasonic testing techniques for the NDE of macrostructural defect states of materials are generally divided into two categories: pulse-echo and through-transmission techniques. In the pulse-echo technique, the transmitting and receiving transducers, which may be combined into a single transducer, are coupled to the same face of the test structure and the reflected wave field (echo) from the defect is analyzed in the time domain or in the frequency domain. The echo from a defect is affected by the defect type, shape, size and orientation, and diffraction of the incident ultrasonic wave. The received signal gives an accurate measure of the defect size only in a limited number of cases. Information on the defect is obtained through interpretation of the signals received at a variety of receiving transducer positions.

In the through-transmission technique, the transmitting and receiving transducers are coupled to the opposite faces of the test structure and the transmitted wave field is analyzed. Although the through-transmission technique is less subject to errors due to defect orientation and scattering, it still suffers from deficiencies such as defect transparency.

For the characterization of cracks perpendicular to the faces of a test structure, special separate transmitting and receiving transducers with an inclined beam angle may be used and the principles of conventional pulse-echo or through-transmission techniques may be applied.

All the above techniques are limited to the analysis of non-overlapping signals. Researchers at LeRC recently introduced an ultrasonic NDE parameter called the "stress wave factor" (SWF). In the SWF configuration separate transmitting and receiving transducers are coupled to the same face of the test structure. An input pulse with a broadband frequency spectrum is applied to the transmitting transducer. The SWF is the number of oscillations (or modifications thereof) in the output signal at the receiving transducer exceeding a

preselected voltage threshold. The SWF is also valid for the analysis of the output signals with overlapping echoes.

Experiments to characterize the SWF signal have shown that it results from the superposition of stress wave field signals that reflect between the top and bottom faces of the structure. Each reflection comes from a different direction and travels a different total ray path length. Reflections may be observed separately if the plate is sufficiently thick, or they may overlap.

The SWF has generally been used to characterize microstructural defects in materials. Work at LeRC has involved the study of experimental SWF output signals generated in plates containing cracks perpendicular to their faces. These studies analyzed the effects of the existence, lateral location and depth of the perpendicular cracks on the SWF signal. Further studies are needed to establish definitive correlations between crack parameters and signal changes, as well as for cracks with different orientations and shapes. The use of scattering theories will also help to develop more quantitative analyses.

REFERENCES

- Williams, J. H., Jr., H. Karagulle and S. S. Lee, "Ultrasonic Testing of Plates Containing Edge Cracks," prepared for Lewis Research Center under Grant NAG3-328, June 1985.

3.7.38 ULTRASONIC TOMOGRAPHY OF HOT METAL

Laboratory: National Bureau of Standards (NBS)

Contact:	Haydn Wadley	Floyd A. Mauer
	Center for Materials	Center for Materials
	Sciences	Sciences
	(301) 921-2956	(301) 921-2950

In collaboration with the American Iron and Steel Institute (AISI), NBS is working on the development of an in-process sensor to measure the internal temperature profile of a hot metallic form (Droney et al. 1984). This sensor would have applications in continuous casting and slab reheating operations (Wadley et al. 1985). Present emphasis is on steel; however, discussions are taking place with the Aluminum Association. The sensor should also be of interest to other primary metals industries.

The velocity of ultrasound in metals such as aluminum and steel is known to be a strong function of temperature (Wadley et al. 1985). A time-of-flight, ultrasonic velocity measurement technique is being studied for application in the sensor. Time-of-flight refers to the elapsed time from the instant ultrasound leaves a source to the instant it reaches a detector. A change in ultrasonic velocity is therefore related to an increase or decrease in travel time of the wave. Once the velocity changes over several different paths and directions have been determined, they are routed to a computational algorithm that reconstructs the internal velocity profile; this can be related to a temperature profile.

Essentially, this is ultrasonic tomography. Although the measurement principle is the same as that of x-ray tomography, there are some important differences. Reflection mode conversion and frequency-dependent attenuation due to grain boundary scattering complicate the ultrasonic case. Fortunately, the reconstruction algorithm can use some a-priori heat flow information to simplify the analysis. This can reduce the number of measurement "scans" needed to three to five, for simple geometric configurations (Wadley et al. 1985).

NBS researchers have designed and tested an experimental system that uses the time-of-flight method. Steel in cylindrical and rectangular shapes has been studied up to 750°C. A major technical problem, however, is coupling the ultrasound to the hot metal. The transmission beam enters the material in a noncontact way as a laser pulse, but an ideal noncontact detector has yet to be developed. Some work has been done using electromagnetic acoustic transducers (EMATs); other work uses momentary multiple contacts with wave guides (see Figure 3.15). This approach keeps the temperature of the receiving transducers within limits.

The group's present work is directed toward: 1) determining accurate values of longitudinal wave velocities as a function of temperature for different steel grades, 2) refining the reconstruction algorithms to account for the frequency dependence of ultrasonic wave attenuation and dispersion as a function of temperature, and 3) extending this approach to higher temperatures (Wadley et al. 1985).

REFERENCES

- Droney, B., et al. "Ultrasonics in Metallurgy," NBS Technical Activities 1984, p. 61.
- Wadley, H. N. G., et al. "Ultrasonic Measurement of Internal Temperature Distribution," Proc. Royal Society (London), July 1985.

3.8 VISUAL-OPTICAL METHODS

FIGURE 3.18. Laser Doppler Velocimetry Measurements in Hot Spots at 182 (Drotsky et al., 1984)

3.8.1 DIAGNOSTIC VIDEO PROBE FOR SEVERE ENVIRONMENTS

Laboratory: Idaho National Engineering Laboratory (INEL)

Contact: W. H. Roach
Manager, Applied Optics
(208) 526-2047

A gas-purged video periscope system with pinhole foreoptics and active cooling is under development. It is designed for quantitative data acquisition in areas where extreme heat, dirt, steam, and other harsh environmental conditions severely limit or preclude the use of conventional optical devices. Potential uses are in nuclear reactors, steel production processes, pulp and paper production, and kiln operations.

3.8.2 HIGH-SPEED INSPECTION SYSTEMS

Laboratory: Pacific Northwest Laboratory (PNL)

Contact: Byron B. Brenden
Electro-Optic System Section
(509) 375-2027

The Electro-Optic Systems Section performs optic and electro-optic R&D in many areas including the design, fabrication, and assembly of large-scale inspection systems. High-speed inspection systems developed for the DOD include a cartridge case measurement eject system, a cartridge case primer depth/lacquer presence system, an EC metal integrity system, and a real-time ultrasonic imaging system. Industrial high-speed inspection systems include a fiberglass panel evaluation system, a golfball orientation/labeling system, and a recyclable bottle inspection system.

In the NDT area, the Electro-Optic (EO) group has developed a high-speed inspection system that interrogates surfaces to detect scratches, folds, dents, etc. The surface flaw system uses a focused line source from a collimated laser to illuminate the full length of a cylindrically shaped part. The part is rotated about its axis to illuminate the entire surface area. In a manner similar to human visual inspection, photodiodes are located to detect light scattered off surface irregularities. Parts that scatter excessive light because of defects are removed from the process line. Background light reflected from the part is monitored as a reference to compensate for long-term laser intensity changes and different surface reflectivities.

Linear array detector signals are used in this surface flaw system to discriminate among various types of defects. Real-time in-process monitoring of defects enables immediate corrective action to minimize material loss and enhance product quality. The surface flaw system was initially designed to monitor the surface quality of cartridge cases and cartridges on U.S. Army production lines; however, the technique is adaptable to a wide variety of parts and surface inspection requirements through fixturing and signal processing modification.

Using the same laser-based surface flaw examination technique in conjunction with two separate EC systems, PNL has developed an advanced cartridge case measurement and eject system (CCMES) to provide 100% inspection of cases, either on-line or in bulkfeed mode. Five case dimensions are measured by an electro-optical profiling system using photodiode arrays. Measurement accuracies and standard deviations are as small as 5 μm ; cases are inspected at the rate of 20/s.

Techniques developed for the CCMES profile monitor can be applied to other high-speed dimensional measurements. Such measurements are applicable where sophisticated quality control, parts sorting, or adaptive process control are needed. The dimensional measurement technique can be applied to the inspection of such items as engine parts, bolts, extruded materials, and pellets. The CCMES system could be readily adapted to installation on any manufacturing line that uses visual inspection and hand-gauging tools for dimensional measurements and flaw determinations. These special high-speed inspection techniques and the associated instrumentation could also be applied to quality assurance and inventory control for continuous manufacturing lines.

PNL has been at the forefront of high-speed inspection technology development. Through the integration of electro-optics, microprocessing and mechanical techniques, PNL scientists and engineers can custom design systems to perform critical measurements and flaw detection according to specific production requirements. Automated systems can be designed to integrate process inspection steps, monitor production for performance requirements, and selectively discard flawed pieces.

Companies interested in exploring the application of high-speed inspection are invited to contact T. J. Doherty, Manager EO Systems Section, (509) 375-3924 or B. Brenden, (509) 375-2027. Specific applications typically involve a preliminary cost-benefit study and engineering analysis to tailor the physical design and operating specifications to the client's intended purpose.

REFERENCES

Cartridge Case Measurement/Eject System, PNL, n.d.

Coleman, W. J., et al. 1975. "On-Line Automatic High Speed Inspection of Cartridge Cases." ASTM Standardization News, Vol. 3, March, 1985.

Electro-Optic Systems Section, Technical Overview, PNL, n.d.

Fiberglass Panel Inspection, PNL, n.d.

High-Speed Inspection, Battelle Technology Transfer Bulletin, n.d.

High-Speed Metallic Cartridge Belt Link Inspection System, PNL, n.d.

Surface Flaw System, PNL, n.d.

Swinth, K. L., R. A. Walker and N. G. Nedrow. 1979. "High Throughput Dimensional Measurements with Electro-Optics." Society of Photo-Optical Instrumentation Engineers, Vol. 193, Optical System Engineering.

3.8.3 LASER SURFACE MAPPER

Laboratory: Idaho National Engineering Laboratory (INEL)

Contact: V. A. Deason
Program Manager
Applied Optics
(208) 526-2501

Various laser surface mapping devices have been completed and are under development that provide detailed surface contours of complex objects. The resolution attainable varies with the type of device. Applications are envisioned in areas such as human body measurements, medicine, modeling and records management.

3.8.4 OPTICAL MEASUREMENT OF SURFACE ROUGHNESS

Laboratory: National Bureau of Standards (NBS)

Contact: Theodore V. Vorburger
Center for Manufacturing Engineering
(301) 921-2158

Optical scattering techniques are widely used by the metalworking industry to monitor the surface roughness (or surface finish) of machined parts. Surface roughness consists of the peaks and valleys characteristic of a particular metalworking process, such as milling, grinding, or lapping. Present optical scattering techniques use an empirical approach, in which the surface roughness of a machined part is compared with calibration standards of known roughness.

NBS researchers are working to put surface roughness measurements by optical scattering techniques on a firm metrological basis. The effort has been twofold: 1) the study of optical scattering phenomena on engineering surfaces, and 2) the development of an appropriate mathematical model capable of deducing roughness parameters solely from optical scattering data (i.e., without the use of comparator standards).

The principle of optical scattering is straightforward. When a beam of light such as laser light is reflected by a rough surface, the radiation is scattered into an angular distribution according to the laws of physical optics (Young et al. 1980). The intensity and pattern of scattered radiation depends on surface roughness parameters, such as peak height and spatial wavelength, and on the wavelength of the incident light beam.

For smooth surfaces, the scattered radiation is localized in the specular direction; however, as surface roughness increases, specular intensity decreases and the intensity of diffuse radiation increases.

NBS has developed an optical instrument to measure the angular distribution of scattered light called DALLAS (detector array for laser light angular scattering). In a typical DALLAS experiment, a beam of He-Ne laser light (wavelength about 0.63 μm) illuminates a rough surface and the scattered

radiation is collected by an array of 87 fiber optic sensors. The signals are sequentially routed to a digital voltmeter and the digitized angular distribution is stored in a minicomputer.

Scattering experiments that were run on DALLAS have been compared with theoretical angular distributions based on digitized roughness profiles measured on the same specimens with a stylus instrument. After increasing the horizontal resolution of the stylus instrument from 0.9 to 0.22 μm , researchers have found fairly good agreement between the two methods.

The stylus technique has long been the standard method of surface topographic measurement. From the degree of displacement of a stylus tip, the technique directly yields a two-dimensional surface profile. However, stylus instruments are fragile and are generally too slow for on-line industrial application. Optical techniques, such as angular scattering, offer the potential for rapid on-line, in-process determination of surface roughness. They also have the capability of tie-in with modern, automated machining.

In addition to the direct scattering experiments with DALLAS, research is under way to solve the inverse scattering problem. Using computational algorithms, researchers have derived the roughness parameters for several prototype sinusoidal-profile precision roughness specimens (a new NBS standard reference material). Preliminary conclusions are that a straightforward Kirchhoff theory is adequate to describe optical scattering of engineering surfaces.

The goal of the group is to develop an on-line optical measurement device and associated algorithms to 1) perform optical scattering measurements of metal surfaces, 2) analyze the resultant data, and 3) deduce surface parameters for full characterization of the surface under examination. An improvement over the more conventional stylus instrument and microinterferometer, this device would offer real-time measurement with possible closed-loop control of some manufacturing processes. A prototype on-line device is currently being developed for surface measurement of wind tunnel roughness at the National Transonic Facility at LaRC. Future devices will probably make use of longer wavelength (10 μm) CO_2 lasers for better application to rougher surfaces.

A portable surface measurement instrument is commercially available; it offers a quicker and more rugged alternative to stylus techniques. The instrument is presently under evaluation by NBS researchers.

REFERENCES

Gilsiin, D. E., et al. 1985. "Surface Texture Characterization by Angular Distributions of Scattered Light." D. V. Thompson and D. E. Chimenti, Eds., Revs. Prog. Quant. Nondestr. Eval. V.4B, 779-788.

Optical Surface Finish Measuring System RM 400 Rodenstock.

Vorburger, T. V., et al. 1984. "Optical Measurement of Surface Roughness." NBS Office of Nondestructive Evaluation, NBS Technical Activities 1984, 3-6.

Vorburger, T. V., et al. 1984 "Surface Roughness Studies with DALLAS - Detector Array for Laser Light Angular Scattering." J. Res. NBS V-89, January - February 3-16.

Young, R. D., et al. 1980. "In-Process and On-line Measurement of Surface Finish." CIRP ANNALS.

Laboratory: Pacific Northwest Laboratory (PNL)
 Contact: Norman Olson
 Materials Department
 (509) 376-2541

3.9 OTHER METHODS

PNL's Materials Reliability Program uses an integrated, multi-disciplinary approach to solving materials reliability problems. This program approach combines process engineering investigations (both in-house and on-site) with component fabrication and field tests selection considerations. First-class measurements of the process environment and nondestructive materials characterization studies are provided. Valuable insights into failure prevention are gained.

PNL's problem-solving approach is illustrated in a recent evaluation project for the pulp and paper industry. This industry makes extensive use of digester pressure vessels to convert wood chips to paper; a highly corrosive liquor is used in the digestion process. Problems with stress-corrosion cracking of these vessels suddenly came to the industry's attention when a digester exploded. Prior to that failure there was no indication of a potential problem. Subsequent inspection of other similar units revealed cracking in some, but not in others. PNL evaluated materials and digester operating conditions on-site at a paper mill. PNL methods were developed for crack detection and monitoring.

The investigation showed that cracking occurs in specific weld areas. Samples were removed for metallographic characterization, and electrochemical probes were used to measure corrosion potential in several vessel locations during operation. Laboratory tests were designed to simulate corrosion and water chemistry conditions. The program resulted in an assessment of the digester materials' susceptibility to cracking. Alternative materials and fabrication techniques were suggested. Researchers are presently exploring modifications of the paper manufacturing process to minimize system corrosion.

3.9.1 ASSESSMENT OF STRESS-CORROSION CRACKING IN DIGESTER VESSELS AND PIPING

Laboratory: Pacific Northwest Laboratory (PNL)

Contact: Norman Olson
Materials Department
(509) 376-2347

PNL's Materials Reliability Center has a unique materials evaluation program that uses an integrated, multidisciplinary approach to solving materials reliability problems. This balanced approach combines process environment investigations (both in-house and on-site) with component fabrication and materials selection considerations. Real-time measurements of the process environment and nondestructive materials characterization studies are providing valuable insights into failure prevention.

PNL's problem-solving approach is illustrated in a recent evaluation program for the pulp and paper industry. This industry makes extensive use of digester pressure vessels to convert wood chips to paper; a highly caustic liquor is used in the digestion process. Problems with stress-corrosion cracking of these vessels suddenly came to the industry's attention when a digester exploded. Prior to that failure there was no indication of a potential problem. Subsequent inspection of other similar units revealed cracking in some, but not in others. PNL evaluated materials and digester operating conditions on-site at a paper mill. NDT methods were developed for crack detection and monitoring.

The investigation showed that cracking occurs in specific weld areas. Samples were removed for metallographic characterization, and electrochemical probes were used to measure corrosion potential in several vessel locations during operation. Laboratory tests were designed to simulate corrosion and water chemistry conditions. The program resulted in an assessment of the digester materials' susceptibility to cracking. Alternative materials and fabrication techniques were suggested. Researchers are presently exploring modifications of the paper manufacturing process to minimize system corrosion.

Design engineers at PNL have developed sophisticated computer methods for calculating stresses in complex structures. Research is also under way to develop NDE methods for a wide range of applications, including instrumentation and procedures for imaging flaws using ultrasonic EC and AE energies. One of the main objectives of materials reliability research at PNL is the integration of laboratory data with NDE test results on real components and structures.

REFERENCES

"Solving Materials Reliability Problems." 1982. Battelle Today, No. 30, November 1982.

3.9.2 EFFECT OF MATERIAL AGING ON NYLON 66 AND KEVLAR 29 STRENGTH DEGRADATION

Laboratory: Sandia National Laboratories (SNL-A)

Contact: I. Auerbach
(505) 844-5535

As part of a systematic study of the effects of environmental factors on nylon 66 and kevlar 29 strength degradation in parachute components, SNL-A is developing NDE techniques that can be used to map mechanical properties over the entire parachute surface. Chemiluminescence, gas chromatography and ultraviolet spectroscopy show potential as NDE techniques.

REFERENCES

Auerbach, I., et al. 1984. "Effect of Material Aging on Parachute Pack Life: A Synopsis of Sandia National Laboratory Studies." Presented at 8th Aerodynamic Decelerator and Balloon Technology Conference, Hyannis, Massachusetts, April 2-4, 1984 (bibliographic entry prepared by Nondestructive Testing Information Analysis Center, September 1985).

3.9.3 EXPLORATORY RESEARCH AND DEVELOPMENT ON NONCONTACTING SENSORS

Laboratory: Idaho National Engineering Laboratory (INEL)

Contact:	J. A. Johnson	B. A. Barna
	Principal Investigator	Program Manager
	Process Diagnostics/NDE	Process Diagnostics/NDE
	(208) 526-9021	(208) 526-6124

Both acousto-optic and electromagnetic-acoustic (EMAT) techniques are being developed to generate and sense acoustic waves in materials without contact to the surface. Laser-generated acoustic waves in molten metals are the focus of FY 1986 work.

3.9.4 HEAVY-SECTION STEEL TECHNOLOGY PROGRAM

Laboratory: Oak Ridge National Laboratory (ORNL)

Contact: Robert W. McClung
Group Leader
Nondestructive Testing Group
(615) 574-4466

The Heavy-Section Steel Technology Program is an engineering research activity conducted by the ORNL for the NRC. The program comprises studies of materials technology for thick-section primary-coolant containment systems of light-water-cooled nuclear power reactors. The studies focus on the behavior and structural integrity of steel pressure vessels containing cracklike flaws. The program emphasizes the use of ultrasonic methods to detect flaws that may propagate under pressure. Current work in the program is divided into nine major areas: 1) fracture methodology and analysis, 2) material characterization and properties, 3) environmentally assisted crack-growth studies, 4) crack-arrest technology, 5) irradiation effects studies, 6) cladding evaluations, 7) intermediate vessel tests and analysis, 8) thermal-shock technology, and 9) pressurized thermal-shock technology.

Although the program was initially developed for the light-water reactor industry, it is applicable to other industries using pressure vessels, pump housings, high-pressure/large-volume gas piping, and other high-pressure containment systems.

REFERENCES

A Bibliography prepared by the Nondestructive Testing Information Analysis Center, December 1984.

3.9.5 HOLOGRAPHIC AND REAL-TIME IMAGING SYSTEMS

Laboratory: Pacific Northwest Laboratory (PNL)

Contact: H. D. Collins
Nondestructive Testing Section
(509) 375-2726

Imaging of flaws is a major research activity at PNL. PNL work includes imaging using acoustical holography, the synthetic aperture focusing technique (SAFT), and image presentation for both EC and microwave methods.

In acoustical holography, computer reconstruction provides the means for storing and integrating several holographic images. A reconstructed stored image is a three-dimensional picture that can be electronically rotated and viewed in an image plane such as a television monitor. Acoustical holography therefore provides full characterization and detailing of buried flaws in solid materials.

EC NDT methods are widely used in industry to solve a variety of materials and product evaluation problems. Because EC tests are nondestructive and require no couplant (liquid) as do the usual ultrasonic tests, 100% rapid inspection can be made to assure uniform quality of critical engineering components.

The EC imaging system developed by PNL utilizes the unique phasography characteristic that EC testing and acoustical holography both exhibit; the phase response of a defect varies linearly with the distance of the defect from the source. To simulate a point source, the PNL imaging system uses a focused coil to confine the time-varying magnetic field to a small area. This reference coil is used with the test coil to feed positional data into a computer reconstruction algorithm.

The basic imaging system consists of a single-frequency EC bridge containing the sense and reference coils integrated with a coherent signal processor. The system is structured to provide both phasographic and focused-probe EC images with three-dimensional format. The simplified block diagram of this hybrid EC imaging system is given in Figure 3.16.

FIGURE 3.16. Eddy Current Phasography and Focused Probe Imaging System

Aluminum and stainless steel test sections with known defects have been successfully imaged. Excellent three-dimensional images were obtained of small fatigue cracks in aluminum (6 mm length, 0.25 mm depth, 0.3 to 4 μ m width).

Whereas EC imaging is only applicable to NDT inspections of conducting solids (metals), the microwave imaging technique developed at PNL can be applied to the inspection of nonconducting materials such as wood, concrete, polymers, etc. Voids in a simulated wall have been clearly imaged in sizes down to the wavelength of the microwave radiation (about 1/3 in.). Metallic objects in the test wall showed with very high contrast. Wires in the size range of about 1 mm could be readily imaged.

Both the EC and microwave imaging techniques represent valuable interpretation aids for NDT inspections in the field. The imaging techniques yield

excellent defect characterization information. The microwave technique represents a relatively novel approach to NDT. Potential applications include the confirmation of rebar in concrete and the detection of defects and moisture in nonconducting composites.

REFERENCES

Collins, H. D., and R. P. Gribble. "Evaluation of Eddy Current '3-D' Imaging Techniques for the Inspection of Cruise Missile Surfaces and Components."

"Solving Material Reliability Problems." 1982. Battelle Today, No. 30, November 1982.

3.9.6 MICROPENETRATION INSTRUMENT

Laboratory: National Bureau of Standards (NBS)

Contact: Robert S. Polvani
(301) 921-2994

A new development at NBS related to material surface property characterization, including wear, is the micropenetration instrument invented by R. S. Polvani. This device forces a small diamond-tip indenter into a surface at loads ranging from 0.1 g to 1 kg, for times ranging from 1 ms to several thousand seconds. The latter time frame would be useful for measuring creep. There is an electronic read-out device attached to the micro-indenter. This makes the device well suited to automated measurements of hardness and other plastic/elastic properties of materials. Applications are expected in measuring coatings and material such as composites.

3.9.7 NONDESTRUCTIVE EVALUATION DEVELOPMENT FOR CERAMIC MATERIALS

Laboratory: Argonne National Laboratory (ANL)

Contact: William A. Ellingson
(312) 972-5066

The reliable use of ceramics as structural components requires effective failure prediction, effective materials characterization, and flaw-detection capabilities. This is particularly important because of the statistical scatter in the strength of bulk-fabricated ceramic materials. Although the average fracture stress may be sufficient, the probability of failure can be relatively high because of the wide variation in fracture stress level. Consequently, material characterization and defect detection of components by NDE is particularly important for ceramics. Efforts to detect variations in material properties and other defects (especially in the green state) may be very useful.

Research is under way at ANL to develop NDE for ceramics, in order to characterize the material in the green state and correlate detected flaws with fracture in the dense state. Work at ANL concentrates on radiographic techniques (x-ray computed tomography, low-kV digital radiography), ultrasonic methods (through-transmission, pulse-echo, and backscatter), and nuclear magnetic resonance imaging for green-state ceramics.

Computed tomography work focuses on mapping density distributions (to detect local variations as small as 0.2 to 0.5%) and on detecting cracks, voids, and inclusions. Ultrasonic work has concentrated on development of through-transmission techniques to characterize green-state ceramics for process control. All systems being developed emphasize digital imaging with a common image display system. Correlation studies of NDE results with fracture behavior utilize special specimens with intentionally introduced defects.

3.9.8 NONDESTRUCTIVE EVALUATION DEVELOPMENT FOR LIGHT-WATER REACTORS

Laboratory: Argonne National Laboratory (ANL)

Contact: David S. Kupperman
(312) 972-5066

The activities in support of light-water reactor (LWR) performance have concentrated on two areas: 1) a feasibility study of ultrasonic volumetric examination of cast stainless steel components and stainless steel welds through a weld overlay, and 2) an evaluation of the applicability of AE monitoring for quantitative leak detection in reactor components under operating conditions.

An informal workshop on the NDE of pipes with weld overlays was held where four teams from industry and other laboratories reconfirmed the difficulty of such inspection and the tendency of crack overcalling. Unpredictable beam distortion, due to the overlay, leads to spurious signals of comparable amplitude to crack reflections. Best results were obtained with 1-MHz longitudinal angle-beam probes.

Four 60-mm-thick cast stainless steel plates with microstructures ranging from equiaxed to primarily columnar grains were examined ultrasonically. It was found that longitudinal sound velocities and the ratios of longitudinal-to-shear wave velocity as a function of position can be used to characterize crystallographic texture. A computer-interfaced mechanical arm with transducer was built to generate color-coded velocity maps and thus effectively characterize the microstructure. Special low-frequency (300-kHz) shear-wave probes significantly improved the signal-to-noise ratio in the ultrasonic inspection of cast stainless steel components.

The leak detection system was used to study leaks from 2-in. ball valves and from flanges; the results were then compared with leak results from intergranular stress corrosion cracks (IGSCCs) and fatigue cracks. The dependence of the acoustical signal on flow rate and frequency content for the valve and the flange was comparable to that of fatigue cracks but different from that of IGSCCs.

Results of laboratory tests, with simulated acoustic-leak signals and signals from field-induced IGSCCs, showed that cross-correlation techniques are a viable method to locate leaks using the GARD/ANL acoustic-leak detection system.

3.9.9 NONDESTRUCTIVE EVALUATION FOR HEAT ENGINE CERAMICS

Laboratory: NASA Lewis Research Center (LeRC)

Contact: Stanley J. Kilma
(216) 433-6019

The increased fuel efficiency resulting from higher allowable engine operating temperatures makes structural ceramics attractive candidate materials for hot-section components in advanced heat engines. These materials, such as silicon nitride and silicon carbide, have excellent oxidation and thermal-shock resistance and good average high-temperature strength. However, current structural ceramics also exhibit wide scatter in strength and relatively low fracture toughness. Poor mechanical properties are generally attributed to defects generated during fabrication. Component reliability can be improved by screening out defective parts through NDE. Fabrication costs can be reduced by utilizing NDE techniques in the early stages of processing to avoid the expense of finishing rejectable parts. If NDE techniques were incorporated into a ceramic materials technology development program, information might be obtained on the source of defects and steps could be taken to minimize their occurrence through improved fabrication methods. Thus, NDE can help reduce the effort expended in a materials research program and shorten the time needed to develop reliable structural ceramics. For these reasons, a program for the NDE of ceramics was established to provide direct support to the recently expanded ceramic materials development effort at the LeRC.

The objectives of the NDE program are to identify and develop conventional and newly emerging methods for application to ceramics research materials and heat engine components and to establish NDE methodology for ceramics process control, properties verification, and degradation assessment. The following describes the ceramic materials research efforts at LeRC.

3.9.9.1 Scanning Laser Acoustic Microscopy

The scanning laser acoustic microscope (SLAM) was used to detect surface and near-surface defects and to reveal patterns of density variations. In the basic operation of the SLAM the longitudinal sound waves are produced by a piezoelectric transducer and transmitted through a couplant (usually distilled

water) to the sample. The angle of the transmitted sound in the sample is given by Snell's law. When the sound reaches the side of the sample opposite the incident-sound source, it displaces the surface to produce a "dynamic ripple." To observe the ripple, a laser beam is scanned over the sample. The laser light, angularly modulated by the surface deformations of the ripple, is reflected to a photodetector and produces a real-time image on a video monitor. The SLAM technique can be used to detect inclusions, cracks, and voids both on and below the surface of the ceramic materials. SLAM can also be used in the interference mode to obtain information regarding bulk density variations. In a sample with constant thickness, the time of travel of ultrasonic waves provide a measure of sound velocity, and velocity can be used to infer material density.

3.9.9.2 Ultrasonic Velocity and Attenuation

Ultrasonic velocity and attenuation measurements were used to characterize density and microstructure in ceramics such as monolithic silicon nitride and silicon carbide. Variations in microstructure had only a slight effect on wave velocity but had a profound effect on wave attenuation. Variations in material density, however, were best studied by examining ultrasonic wave velocity.

3.9.9.3 Radiography

X-ray methods were used to evaluate ceramic materials in all stages of specimen fabrication. Radiographs of ceramic samples taken after firing show variations indicative of bulk density changes through the volume of the samples. The variations are caused by differences in x-ray absorption, which is directly proportional to the number of atoms encountered by the beam as it passes through the material. For this reason, radiographic techniques are also excellent for detecting foreign particles, particularly those with relatively high density compared to the material in which they reside. X-ray radiography is a well-developed and a relatively fast and easy technique to apply. The use of radiography at various stages of a production process is an excellent method to detect processing problems and ensure the production of uniform products.

3.9.9.4 Fracture Mechanics and NDE Reliability

The reliability of an NDE procedure is defined as the efficiency of that procedure to detect flaws of a specific type and size. After NDE a particular component cannot be called entirely free of flaws simply because none were found, but the part is probably free of defects of a specific type and size.

The need to assess quantitatively the reliability of flaw detection has arisen from the application of fracture mechanics principles to the design of critical parts. The fracture mechanics concept assumes that flaws will exist, and then quantitatively describes their effects on strength. Thus, a critical crack size is defined for a particular material and loading condition. The role of NDE is to assure that flaws corresponding to the critical crack size for fracture at the design load are absent when the part is put into service.

The use of fracture mechanics concepts emphasizes the ability of nondestructive inspection to detect small defects, and the need to determine the practical reliability of a particular NDE procedure when that procedure is used to detect flaws of a specific size and type. If the design is such that the critical crack size based on design loads is greater than the smallest flaw that can be reliably detected, the inspection process can be used.

3.9.9.5 Thermoacoustic Imaging

Like the x-ray technique, thermoacoustic imaging can be used in a non-contacting, noninvasive mode. Commonly referred to as photoacoustic microscopy, photoacoustic spectroscopy, or thermal-wave imaging, the technique essentially measures relative differences in surface and near-surface thermal properties of the material being evaluated. The absorption of intensity-modulated electromagnetic radiation focused at any point on the sample creates localized cyclic heating and cooling, which generates sound waves. The amplitude and phase of these waves can be measured at another point on the specimen surface with a piezoelectric crystal or in the surrounding medium by a sensitive microphone. Thermoacoustic waves are commonly generated by absorption of laser light or an electron beam, but other forms of electromagnetic energy such as microwaves, infrared, or x-rays might also be used. Laser methods are also

being considered for picking up signals. This increases the versatility and flexibility of the thermoacoustic technique.

REFERENCES

Kilma, S. J. 1984. "NDE for Heat Engine Ceramics." Prepared for the Twenty-Second Automotive Technology Development Contractors' Coordination Meeting, Dearborn, Michigan, October 29 to November 2, 1984.

3.9.10 NONDESTRUCTIVE EVALUATION OF ACID RAIN DAMAGE TO MATERIALS

Laboratory: Argonne National Laboratory (ANL)

Contact: C. Arthur Youngdahl
(312) 972-5066

The effect of the acidic outdoor environment on structural and ornamental materials is currently of much concern. These materials include concrete, brick, mortar, natural building stone, paints, and metals. They are used in the construction of buildings, roadways, bridges, guardrails, electrical towers, lighting fixtures, signs, memorials, and monuments. Modes of materials damage include corrosion, dissolution, microcracking, and the formation of unsightly chemical products on surfaces. An evaluation of the rates of damage is under way. The effort is part of a federal program designed to develop the quantitative understanding needed to improve control of acidic deposition.

ANL participates in this program by 1) evaluating methods to assess such damage; and 2) applying appropriate methods, under the national program, to materials that have suffered damage from the outdoor environment. Nondestructive methods that were evaluated include techniques that employ 1) EC to assess depths of corrosion pits and grooves and thicknesses of corrosion films; 2) x-ray fluorescence for in situ analysis of corrosion products and deposits; 3) nuclear magnetic resonance for measurement of moisture and reaction products within porous solids; 4) ultrasonic surface waves to detect the presence of microcracks; and 5) laser-optical interferometry to measure surface roughening and material loss. Traditional methods have also been adapted for the assessment program, including gravimetric monitoring of exposure-test specimens and material coring and surface sampling for chemical extraction and analysis. Selected methods of nondestructive and destructive analysis have been applied by ANL in this program routinely since 1984.

The existing facilities and expertise may be used for other work in cooperation with commercial and institutional organizations. Currently, surface

material loss studies are conducted with the Illinois Institute of Technology. The University of Notre Dame cooperates with ANL in porosity studies of marble and limestone that are of interest to ASTM Committee C.18 and to architectural engineering firms.

3.9.11 NONDESTRUCTIVE EVALUATION OF ADVANCED CERAMIC COMPOSITE MATERIALS

Laboratory: Idaho National Engineering Laboratory (INEL)

Contact:	J. B. Walter	L. A. Lott
	Co-Principal Investigator	Co-Principal Investigator
	Materials Characterization	Materials Characterization
	(208) 526-0033	(208) 526-6436

The DOE supports research in the production of advanced ceramic composites for application in certain segments of the fossil energy industry. This includes support for the development of NDE techniques for characterizing and qualifying these materials for use.

The work at the INEL is concerned with sintered composites of SiC fibers and whiskers in matrices of SiC and Si_3N_4 . The suitability of these materials for the intended applications depends on the presence of localized flaws, but also on microstructural features such as fiber or whisker size and distribution, matrix grain size, porosity, and bonding between the fiber or whisker and the matrix.

The NDE effort focuses on ultrasonic examination. The initial study will investigate the effects of the material microstructure on acoustic velocity and attenuation, and also on acoustic scattering. The acoustic scattering technique requires access to only one side of a sample, and has application for less restrictive geometries than the parallel sides required for the attenuation and velocity measurements. Work under way for another program suggests that acoustic scattering may be sensitive to many of the noted microstructural features (Bureau of Mines 1985). Future study will extend these techniques to detect microstructural anomalies and other flaws. These investigations will use neutron and microfocus x-ray radiography as corroborative techniques.

REFERENCES

"Strategic and Critical Materials Annual Report, May 1985," Bureau of Mines, Department of the Interior, Contract J0134035, Idaho National Engineering Laboratory, Department of Energy, Idaho Falls, ID 83415.

3.9.12 NONDESTRUCTIVE EXAMINATION OF CERAMIC MATERIALS

Laboratory: Oak Ridge National Laboratory (ORNL)

Contact: Robert W. McClung
Group Leader
Nondestructive Testing Group
(615) 574-4466

The use of structural ceramics in engineered components, particularly components that require the joining of fabricated ceramic shapes into larger or more complex configurations, requires the development of NDE procedures to assure the integrity of the components themselves and the joints between components. Flaws in the material or the joints (made by brazing, fusing, or other processes) will affect such parameters as fracture toughness and strength. Most NDE techniques have focused on metals and are not directly applicable to ceramics. It is necessary, for example, to examine ceramics with ultrasonic waves of considerably higher frequency than are normally used in metals. This is because of the higher wave velocity and much smaller critical flaw size in ceramics. Much of NDE technology, however, can serve as a useful starting point for the development of examination techniques for ceramics. ORNL researchers are developing radiographic and high-frequency ultrasonic techniques for the examination of ceramics to detect, locate, and size critical flaws and to measure nondestructively the elastic properties of the host material.

Work has concentrated on developing an ultrasonic system for generating and detecting elastic waves of high frequency (above 50 MHz). Silicon nitride, for example, will have flaws ranging from 25 to 100 μm . If an average flaw diameter of 50 μm is assumed, then the frequency at which maximum scattering occurs can be calculated to occur at about 66 MHz. Below this frequency, the scattering decreases with the fourth power of the frequency and is insensitive to flaw shape. For these reasons, high-frequency ultrasonic equipment is necessary to study the effect of flaw size and concentration on the mechanical properties of ceramics.

REFERENCES

Oak Ridge National Laboratory, Program Overview, 1985.

3.9.13 NONDESTRUCTIVE EXAMINATION OF GRAPHITE MATERIALS

Laboratory: Oak Ridge National Laboratory (ORNL)

Contact: Robert W. McClung
Group Leader
Nondestructive Testing Group
(615) 574-4466

Techniques have been developed at ORNL to examine graphite materials. Graphite is a commonly used substance in both nuclear and space applications. ORNL studies have concentrated on ultrasonic and radiographic examination techniques. The study of ultrasonic attenuation (as a function of frequency) and velocity has proven to be beneficial for the improved detection of flaws in graphite, and for determining the relationship of flaw size and population to the elastic properties and strength of the sample tested. Ultrasonic work has also included the development of signal-processing techniques using frequency analysis and scattering theory to improve flaw characterization.

Research in radiographic NDE methods has demonstrated the usefulness of this technique for the examination of graphite materials. Direct measurement of transmitted x-radiation allows the measurement of graphite density to within 0.1% accuracy. The use of very low-voltage radiographic techniques on thin, low-density graphite components has been shown to be useful for the detection of flaws and nongraphitic inclusions.

REFERENCES

McClung, R. W. 1985. Summary of Nondestructive Examination Technology at Oak Ridge National Laboratory.

4.0 INDUSTRY REVIEW

Descriptions of NDT R&D and facilities of the federal laboratories surveyed were grouped by NDT method, assembled into a Preliminary Findings Report, and sent to selected industry representatives for review. This section summarizes the industry review comments received; comments were incorporated into this final report as much as possible.

The Preliminary Findings Report was sent to fifteen industry representatives. Although the number of reviewers was limited, the review process attempted to encompass a wide range of industry groups, including both large and small companies and organizations, and users and manufacturers/servicers of NDT equipment. The following companies and organizations were asked to review the Preliminary Findings Report:

- Amoco Oil Company
- Babcock & Wilcox Company
- EPRI NDE Center
- Ford Motor Company
- Garret Turbine Engine Company
- Gaston County Dyeing Machine Company
- Hellier Associates
- Kaiser Center for Technology
- Lockheed Missiles and Space Co., Inc.
- Magnaflux Corporation
- United Merchants and Manufacturers, Inc.
- United States Steel Corporation.

In addition, a presentation on the federal laboratory survey was given at the annual conference of the Nondestructive Testing Management Association (NDTMA). The presentation was intended to introduce the project's purpose and to familiarize key high-level industry representatives with federal laboratory technologies.

Industry representatives were asked to comment on the following:

- overall impressions of the exercise and report
- specific items most useful/applicable to their industry and their company
- the novelty and perceived state of the technologies relative to current industrial practice
- suggestions for improving and distributing this or future reports
- the appropriateness of, and level of industrial interest in, any of the following five activities as a means to facilitate transfer of federal NDT technology to industry:
 - single topic compendia or anthologies (e.g., on NDT methods or industrial NDT problems)
 - third-party authorship of papers for journals geared to middle and upper management
 - personnel exchanges (from industry to labs and from labs to industry)
 - engineering development prototypes (i.e., proof-of-concept of new technology in industrial settings)
 - workshops.

General impressions on the survey and report were very favorable. It was valued as a relatively comprehensive compendium or synopsis of federal laboratory NDT activities and capabilities, as a guide to information sources, and as a resource on technologies of interest to manufacturing industries.

Among the positive aspects mentioned concerning the survey and report were:

- the broad scope and collection of a multitude of R&D efforts in a single volume
- the inclusion of some items of which the reviewers were unaware

- the common format of work descriptions and the general conciseness of entries (some pointed out that even shorter entries may be useful)
- the inclusion of brief overviews of current NDT activities and capabilities at the laboratories, which provided a useful perspective
- the organization by NDT method
- the possible avoidance of duplicating sponsored research.

Relative to current industrial practice, technologies were seen as state-of-art at various stages of development. Work ranges from the initial stages of development to commercialization. One reviewer noted that research tends to be duplicated unnecessarily. While some variations are being explored by the federal laboratories, some of the concepts could be commercialized earlier.

Little indication was made of specific technologies or work efforts of interest, although some reviewers indicated they would follow up with selected items. One reviewer thought the report contained little in his field of interest (i.e., NDE of concrete).

Items cited to enhance the usefulness of the report include:

- indication of the time frame of the study
- software codes for analysis or control of equipment
- instructions on how to follow up with leads and information on fees to be paid for access
- a cross-referencing or indexing scheme to allow identification of efforts related to specific NDT problems
- specific details on measurement ranges and accuracies that are needed for any measurement technology.

Several reviewers pointed out certain areas of federal laboratory work not contained in the report, but of interest to them. For example:

- work at U.S. Navy laboratories (e.g., work on replacing radiography with ultrasonics, which could impact details of the ASME Section III code)

- work with composite/adhesive/resin inspection (e.g., at LaRC)
- work at U.S. Department of the Interior and U.S. Army laboratories, particularly NDE work on concrete.

In the last category of comments, a variety of views were expressed concerning the means of transferring federal NDT technology to industry. With the exception of workshops, all of the five items listed above were mentioned as the most successful way to accomplish transfer of technology to industry. The range of views is probably due to the differing character and interests of organizations and is perhaps a reflection of the comment made by one reviewer that adequate technology transfer must be determined by the recipient. In general, reviewers tended to think that the information presented at workshops was either dated or of insufficient depth. Workshops were mentioned as possible follow-up to a compilation of work relevant to specific NDT problems.

5.0 CONCLUSIONS AND RECOMMENDATIONS

This section summarizes the findings and conclusions about the survey effort, the technologies described, and the industrial review. Recommendations are made for conducting similar surveys and follow-up activities to promote technology transfer to industry.

5.1 CONCLUSIONS

The following are major conclusions regarding the survey:

- NDT technology proved to be a wise choice of topics; a considerable amount of federally supported R&D and industrial interest in the subject were found.
- Expanding the scope of laboratories increased the coverage of federal laboratory NDT work but also limited the subsequent follow-up and analysis of technologies. More effort could have been profitably expended in this area.
- A number of trade-offs are involved in conducting R&D surveys. The most important factors include 1) the topic of the survey, 2) the number of laboratories surveyed, 3) the range of applicable industries, and 4) the development stage of the technologies. As indicated, expanding the number of laboratories surveyed may identify more related work, but it may limit the follow-up and analysis efforts afterward. The wider the scope of industries that are included, the less the information may be of interest to individual industries. Similarly, choosing a broad or narrow focus on the stage of technological development involves trade-offs. It may be advantageous for individual industries or organizations to know about technologies at different stages of development. Focusing on technologies ready for commercialization may emphasize activities of which many people are already aware; however, it is critical at this stage for information to be disseminated and for industry to become

involved to transfer the technology. Because of these trade-offs, careful consideration of the survey parameters and some flexibility in conducting the survey are required.

- Several constraints and issues related to transfer of federal technology to industry were revealed throughout the survey. These include:
 - normal risks associated with transfer of any technology; for example, the technology may prove uneconomical or may not be sufficiently developed or expectations concerning it may be too high
 - lack of time, staff and funds at the laboratories to devote to technology transfer
 - preference of R&D people to conduct R&D rather than technology transfer
 - differing technical and organizational backgrounds between individuals
 - differing levels of technological expertise and facilities among organizations
 - security considerations
 - lack of information on technologies.
- In compiling review comments on technology transfer methods, no particular method was consistently rated the highest. Personnel exchange or transfer of a working prototype were often mentioned as effective means of facilitating technology transfer.

5.2 RECOMMENDATIONS

This study makes the following recommendations:

- Surveys of Federal laboratory R&D should be continued. This may include periodic follow-up of topical surveys conducted previously.
- In conducting such surveys, the following should be considered:

- The topics should be chosen carefully. Too narrow or broad a topic can make the survey difficult and limit its usefulness. Federal laboratories should be conducting R&D in that area and it should be of interest to industry.
- The broadest possible coverage of laboratory work should be attempted and all laboratories should be visited. More input from the laboratories should be requested, particularly with respect to the methods and procedures to follow-up on technologies and to gain access to laboratory facilities. The bulk of the survey effort should be to characterize the technologies, to obtain additional or follow-up information, and to analyze their applications.
- Alternative approaches to industrial review of findings should be considered, perhaps independently or after the survey is completed. The time and effort spent on industrial review might be better spent on identifying and characterizing R&D activities. Time might be provided for additional survey and follow-up after the industrial review cycle.

APPENDIX A

POTENTIAL APPLICATIONS OF FEDERAL LABORATORY
NDT ACTIVITIES IN U.S. MANUFACTURING INDUSTRIES

APPENDIX A

POTENTIAL APPLICATIONS OF FEDERAL LABORATORY NDT ACTIVITIES IN U.S. MANUFACTURING INDUSTRIES

TITLE	LABORATORY/CONTACT	FOCUS OF LABORATORY WORK REPORTED	POTENTIAL APPLICATIONS
<u>Acoustic Emission (AE)</u>			
1. A Continuous Acoustic Emission Monitoring System for Flaw Detection	PNL P. H. Hutton (509) 375-2157	System development	Monitoring of acoustic properties of metals for the surveillance of high-pressure vessels, pipes, and boilers.
2. Acoustic Emission in Metallurgy	NBS R. B. Clough (301) 921-2965	Technique development, evaluation, and experimental application	Acoustic energy measurement in metals for monitoring rapid solidification processing.
3. Acoustic Emission Source Location System	NBS N. N. Hsu (301) 921-3646	System development	Flaw detection, process control, materials characterization.
4. NDE of Tool Wear and Chip Formation on-line Sensor Developments	NBS K. W. Yee (301) 921-3381	Instrument development & evaluation	Acoustic response measurement for tool wear monitoring in metal-working operations (e.g., cutting).
<u>Eddy Currents (EC)</u>			
1. Advanced Eddy Current Coil Excitation and Signal Processing	AFWAL J. Moyzis (513) 255-5309	Pulsed EC theory and instrument development	Inspection of low-conductivity materials used in engine components, crack depth determination.
2. Eddy Current Examination of Steam Generator Tubes/Surry Steam Generator Facility	PNL S. R. Doctor (509) 375-2495	Determination of reliability of EC inspection methods, test bed facility	Conductivity/permeability measurements in non-ferromagnetic alloy tubes for improved inspection, operator training and guidelines for EC testing.
3. Eddy Current Instrumentation Development	PNL J. M. Prince (509) 375-2469	Instrument development	Conductivity/permeability measurement in metals for on-line, high-speed thicknesses inspections of layered samples and machined parts.
4. Eddy Current Inspection Research	ORNL C. V. Dodd (615) 574-4839	Multifrequency signal processing; probe development	Flaw detection in ferromagnetic and nonferromagnetic materials such as superconductor cable sheath, steam generator tubing, and stainless steel plate welds.

APPENDIX A (contd)

TITLE	LABORATORY/CONTACT	FOCUS OF LABORATORY WORK REPORTED	POTENTIAL APPLICATIONS
<u>Eddy Current (contd)</u>			
5. Eddy Current Jet Engine Disc-Crack Monitor	LeRC J. P. Barranger (216) 433-6019	Sensor & inspection technique development & application	Real-time inspection of high-temperature machinery (e.g., engines, processing equipment).
6. Eddy Current Probe Development	AFWAL D. Chimenti (513) 255-5309	Probe development	Flaw detection in metal aircraft & engine components; especially useful for automated scan, crack detection systems.
7. Eddy Current Sensors for Small Flaw Detection in Metallic Components	AFWAL D. Chimenti (513) 255-5309	Probe development	Small flaw detection in metallic engine components, complex geometries.
8. FMR Advanced Surface Flaw Detection Methods	AFWAL J. Moyzis (513) 255-5309	Probe development	Surface flaw detection in metallic engine components, complex geometries.
<u>Electrical</u>			
1. Cure Monitoring in Polymers Via Dielectric Spectroscopy	NBS F. I. Mopsik (301) 921-3851	Equipment development & experimental application	Measurement of dielectric loss in polymers for polymer cure monitoring.
2. Microwave Measurement of the Complex Dielectric Tensor of Anisotropic Slab Materials	LLNL R. King (415) 422-7045	Experimental evaluation	Dielectric tensor determination in semi-transparent anisotropic materials for physical & mechanical property measurements (e.g., moisture content in wood).
<u>Magnetic Methods</u>			
1. Ferrography of Wear Debris Particles	NBS A. W. Ruff (301) 921-2966	Technique development & standardization	Measurement of density of wear particles and particle size for wear monitoring in mechanical systems.
2. Influence of Fatigue and Stress on Magnetic Properties	Ames R. B. Thompson (515) 294-7803	Experimental evaluation	In-process monitoring of metal processes (e.g., hardening & tempering) by measurement of magnetic properties.
3. Magnetic Methods Nondestructive Testing	NBS L. Swartzendruber (301) 921-2955	Theoretical and experimental development; standards development	Inspection of ferromagnetic materials.

APPENDIX A (contd)

TITLE	LABORATORY/CONTACT	FOCUS OF LABORATORY WORK REPORTED	POTENTIAL APPLICATIONS
<u>Radiography & Radiation</u>			
1. Direct Conversion X-ray Imaging Detectors	NBS M. Kuriyama (301) 921-2986	Development and characterization of equipment	inspection of lightweight materials, electronics.
2. Dynamic Radiographic Imaging Using High-Speed Video	LANL L. Bryant (505) 667-8721	Capability and development of systems in dynamic radiographic imaging	Evaluation of performance and function of mechanical systems (e.g., imaging boiling action of liquids, compressor operation, thermal battery operation, metal forming and other dynamic manufacturing processes).
3. High Average Power Induction Accelerator	LLNL D. L. Brix (415) 422-7045	Equipment development	Radiographic applications.
4. High Resolution Nonfilm Radiography	AFWAL L. R. Gully (513) 255-3612	System development	Manufactured parts inspection, particularly relatively thin (1 in. or less) metallic or composite components.
5. Low-Energy Radiography	LLNL S. Fletcher (415) 423-4267	Capabilities, research programs	Radiographic applications.
6. Materials Characterization with Small-Angle Neutron Scattering	NBS C. J. Glinka (301) 992-3634	Technique development, evaluation, and application	Materials characterization; in-process monitoring of ceramics and metal alloys.
7. Microfocus Rod-Anode X-ray Unit Development	ORNL B. E. Foster (615) 574-4837	System development, evaluation and application	Radiographic inspection requiring high resolution or having limited access (e.g., steam generator welds)
8. NBS Center for Cold-Neutron Research	NBS R. S. Carter (301) 921-2421	Facility, industrial opportunities	Materials (ceramics, metals, polymers) characterization.
9. Radiography and Computer Tomography Capabilities	SNL O. J. Burchett (505) 844-3500	Capabilities	Wide-scale radiographic inspection applications.
10. Radiographic Detectability Limit Research	LeRC G. Y. Baskin (216) 433-6019	Comparative studies of techniques	Wide-scale radiographic inspection applications (e.g., defect evaluation in ceramics, engines, and other structures).
11. Radiographic Materials Characterization System	LLNL J. Haskins (415) 422-4267	Software	Wide-scale radiographic applications, imaging of radiographic inspections.

APPENDIX A (contd)

TITLE	LABORATORY/CONTACT	FOCUS OF LABORATORY WORK REPORTED	POTENTIAL APPLICATIONS
<u>Radiography and Radiation (contd)</u>			
12. Research Investigations in Industrial Radiology	NBS J. W. Motz (301) 921-2201	Experimental evaluations, industrial opportunities	Wide-scale radiographic applications.
13. Residual Stress Measurements with Energy Dispersive X-ray Diffractometry	NBS M. Kuriyama (301) 921-2986	System development	Weld inspection, control of heat treatment, cold-working steel operations.
14. Tomographic Densitometry	INEL J. R. Fincke (208) 526-2031	Technique development, equipment	Two-phase flow measurement.
15. X-ray Tomographic System Development	LANL D. Elliot (505) 667-6291	Capabilities, system development	Broad radiographic applications.
<u>Thermal</u>			
1. Early Corrosion Detection of Steel Under Protective Coatings Using Thermal-Wave Imaging	NBS T. Nguyen (301) 921-3208	Experimental evaluation	Detection of steel corrosion under protective coatings.
2. Thermal-Wave Imaging of Surface and Near Surface Defects in Ceramics	NBS G. S. White (301) 921-3277	Experimental evaluation	Defects detection in ceramics production.
<u>Ultrasonics</u>			
1. Acoustoelastic Measurement of Stress and Texture	Ames R. B. Thompson (515) 294-7803	Theoretical development, experimental evaluation	Measurement of residual stress and texture of metals (e.g., aluminum).
2. Advanced Ultrasonic Inspection Instrument	PNL A. Birks (509) 375-2138	Prototype model production and equipment specification	In-service or field inspection of metallic and composite components (e.g., aircraft, nuclear components).
3. An Automated Ultrasonic Data Acquisition System	SNL J. Gieske (505) 844-3500	System description	Defect measurement for general NDE applications.
4. An Ultrasonic Thickness Gauge	SNL W. Shurtleff (505) 844-3500	Instrument description	Portable thickness gauge, possible measurement of multilayered materials.

APPENDIX A (contd)

TITLE	LABORATORY/CONTACT	FOCUS OF LABORATORY WORK REPORTED	POTENTIAL APPLICATIONS
<u>Ultrasonics (contd)</u>			
5. Automated Multiviewing Ultrasonic Transducer	Ames D. O. Thompson (515) 294-7803	Prototype instrument development and application, data processing	Wide-scale application for flaw detection (e.g., potential for use in automated inspection of welds, forgings, and metallic components).
6. Automated Ultrasonic Test Bed	LLNL J. Brase (415) 422-6992	Facility, software	High-resolution inspection of various materials (metals, ceramics, composites) including large components and complex geometries.
7. Automated Welding NDE	INEL J. O. Bolstad (208) 526-1753	System development	Automation, control of welding processes.
8. Computer Automated Ultrasonic Inspection System	AFWL E. Wheeler (513) 255-515	System development (hardware & software)	Automated ultrasonic inspection applications (e.g., manufactured engine and aircraft components); has been demonstrated for forging, composite structure.
9. Concurrent Ultrasonic Weld Inspection	INEL J. A. Johnson (208) 526-9021	System development and application	Weld inspection for multipass welds.
10. Crack Characterization	INEL J. A. Johnson (208) 526-6124	Experimental evaluations	Potential broad applications to crack detection (e.g., in-service examination of structures, components, welds, castings, forgings, and pressure containing systems).
11. Evaluation of Effectiveness of Heat Treatment on Strength of Aluminum Alloys	LeRC J. S. Heyman (804) 865-3036	Development/experimental evaluation	Elastic property measurement in aluminum, titanium weld metal; fatigue measurement.
12. Flaw Characterization with Scanning Laser Acoustic Microscopy	LeRC E. R. Genearzio (216) 433-6019	Technique description and application	Inspection and characterization applications for ceramics, metals, composites and electronics.
13. Flaw Detection in Concrete Using Impact-Echo Techniques	NBS N. J. Carino (301) 921-2648	Technique development and standardization	Concrete inspection and characterization in buildings, highway construction, etc.
14. Focused Reflection Acoustic Microscope	LLNL R. Streit (415) 422-7045	Facility (Instrumentation)	High-resolution inspection of medium-sized components (e.g., ceramics, metals, composites, electronics).
15. Internal Temperature Profile of Hot Steel	PNL D. K. Lemon (509) 375-2306	Sensor and technique development	Monitoring of internal temperature of elastic solids at high temperatures (e.g., on-line monitoring of continuous casting).

APPENDIX A (contd)

TITLE	LABORATORY/CONTACT	FOCUS OF LABORATORY WORK REPORTED	POTENTIAL APPLICATIONS
<u>Ultrasonics (contd)</u>			
16. Nondestructive Evaluation Development for Composite Materials	ANL R. A. Roberts (312) 972-5066	Technique development	Microstructure characterization and flaw detection (porosity, microcracking) for fiber-reinforced composite materials.
17. Nondestructive Evaluation of Composite Laminates by Leaky Lamb Waves	AFWAL D. E. Chimenti (513) 255-5309	Theory and instrument development	Inspection of fiber-reinforced structural materials.
18. Nondestructive Evaluation of Laminated Panels	AFWAL R. L. Crane (513) 255-5561	Theory and technique development	Inspection of laminated structural materials, especially developed to detect flaws in edges.
19. Nondestructive Evaluation of Integrally Fabricated Turbine Rotors	Ames R. B. Thompson (515) 294-7803	Experimental survey of techniques, theory development	Inspection of solid-state bonds (e.g., pinch welds, inertia welds, resistance welds); turbine rotor fabrication and repair.
20. Nondestructive Systems for On-Line Monitoring of Erosive Wear	ANL C. A. Youngdahl (312) 972-5066	Sensors and system development and application	On-line monitoring of erosive wear of high-temperature metallic process lines and vessels (e.g., heat exchanger piping of fluidized-bed combustion systems).
21. Phase Insensitive Transducers/Composite Materials NDE	LaRC J. S. Heyman (804) 865-3036	Development, experimental evaluation	Detection/evaluation of defects and changes in properties of composite materials.
22. Pulse-Echo Acoustic Microscopy for Inspection of Silicon Carbide Components	INEL D. C. Kunerth (208) 526-0103	Technique development and application	Lifetime prediction studies and ceramics quality control for heat exchanger ceramics
23. Pulsed Phase Locked Loop Interferometer	LaRC J. S. Heyman (804) 865-3036	Technique description and application	Evaluation/monitoring of bolt preloading, stress, and material properties.
24. Real-Time, In Situ, Nondestructive Monitoring of Solidification Interfaces	NBS R. L. Parker (301) 921-2961	Technique development, experimental evaluation	Characterization of solidification interfaces in metal; monitoring and control of continuous casting.
25. Special Low-Frequency Transducers for Concrete Inspection	ANL K. J. Reimann (312) 972-5066	Transducer development and evaluation	Inspection of concrete structures (e.g., thickness, aggregate size, internal delaminations).
26. Standards for Ultrasonic Measurement of Residual Stress	NBS D. Eltzen (301) 921-3646	Standards development	Residual stress measurement in metals (e.g., in aircraft/spacecraft, welding, heat treating).

APPENDIX A (contd)

TITLE	LABORATORY/CONTACT	FOCUS OF LABORATORY WORK REPORTED	POTENTIAL APPLICATIONS
<u>Ultrasonics (contd)</u>			
27. Stress Level Measurement in Rail Car Wheels	LaRC J. S. Heyman (804) 865-3036	Technique development, evaluation and validation	Confirmation of proper heat treatment of rail car wheels, detection of overheated wheels in service; stress measurement in structures (e.g., pressure vessels, bridges).
28. Synthetic Aperture Focusing Technique for Ultrasonic Imaging	PNL S. R. Doctor (509) 375-2495	System development for defect detection	Computerized ultrasonic 3-D imaging and characterization; useful where volumetric image is desired (e.g., nuclear/fossil pressure retaining systems).
29. Ultrasonic and Acoustic Emission Transducer Developments	NBS D. G. Eitzen (301) 921-3646	Calibration services, design and evaluation of equipment, standards development	Broad ultrasonic/acoustic applications.
30. Ultrasonic Characterization of Porosity in Cast Aluminum	Ames J. H. Rose (515) 294-8152	Theoretical development, experimental evaluation	Aluminum process control, quality control for aluminum castings.
31. Ultrasonic Evaluation of Ceramic and Rapidly Solidified Alloy Material and Joints	INEL L. A. Lott (208) 526-6436	Experimental evaluation of microstructural features	Measurement of bond quality and material properties in ceramics and rapidly solidified alloy materials.
32. Ultrasonic Evaluation of Material Properties	LaRC A. Vary (216) 433-6019	Theoretical model development	Correlations between ultrasonic and mechanical properties of metals and ceramics for materials development and quality control.
33. Ultrasonic High-Speed Data Acquisition System	SNL W. Shurtieff (505) 844-3500	System description and application	Flaw detection and characterization including automated inspections of metals (welds, forging, castings) and composites.
34. Ultrasonic Inspection of Material Microstructure	LaRC E. R. Generazio (216) 433-6019	Theory, experimental evaluations	Verification of heat treatment of metals.
35. Ultrasonic Inspection Research and Development	ORNL R. W. McClung (615) 574-4466	Capabilities, research programs	Broad ultrasonic inspection applications.
36. Ultrasonic Measurement of Surface Roughness	NBS G. V. Blessing (301) 921-3646	Experimental evaluation	Surface roughness measurements, contactless NDE.

APPENDIX A (contd)

TITLE	LABORATORY/CONTACT	FOCUS OF LABORATORY WORK REPORTED	POTENTIAL APPLICATIONS
<u>Ultrasonics (contd)</u>			
37. Ultrasonic Testing of Plates Containing Edge Cracks	LeRC A. Vary (216) 435-6019	Experimental evaluations	Broad application for detection and evaluation of cracks in materials (e.g., in metal fabrication).
38. Ultrasonic Tomography of Hot Metal	NBS H. Wadley (301) 921-2956	Sensor development and application	Temperature profile measurement in hot metal forms (e.g., in monitoring and control of continuous casting of steel).
<u>Visual-Optical</u>			
1. Diagnostic Video Probe for Severe Environments	INEL W. H. Roach (208) 526-2047	System development	Visualization of high-temperature, hostile processes (e.g., in nuclear reactors, steel production, pulp and paper production).
2. High-Speed Inspection Systems	PNL B. B. Brenden (509) 375-2027	Custom design of inspection systems	Dimensional measurement and surface inspection (flaw detection) of layered samples and machined parts.
3. Laser Surface Mapper	INEL V. A. Deason (208) 526-2501	Identification and development of devices	Modeling, record keeping, medical applications.
4. Optical Measurement of Surface Roughness	NBS T. V. Vorberger (301) 921-2658	Experimental evaluations, mathematical modeling, equipment development	Surface roughness measurements on all surfaces.
<u>Others</u>			
1. Assessment of Stress Corrosion Cracking in Digester Vessels and Piping	PNL N. Olson (509) 375-2138	On-line continuous monitoring, problem solving, consulting services	Detection and evaluation of cracks in process equipment (e.g., in nuclear, paper, and chemical industries).
2. Effect of Material Aging on Nylon 66 and Kevlar 29 Strength Degradation	SNL I. Auerbach (505) 844-5535	Systematic survey of test methods including NDE methods	Measurement of environmental effects of nylon, kevlar, and polymer materials.
3. Exploratory R&D on Noncontacting Sensors	INEL J. A. Johnson (208) 526-9021	Exploratory R&D	Noncontact and high-temperature inspections.

APPENDIX A (contd)

TITLE	LABORATORY/CONTACT	FOCUS OF LABORATORY WORK REPORTED	POTENTIAL APPLICATIONS
Others (contd)			
4. Heavy-Section Steel Technology Program	ORNL R. W. McClung (615) 574-4466	Fracture studies	Steel pressure vessels, heavy-steel sections (e.g., pipes and pumping).
5. Holographic and Real-Time Imaging Systems	PNL H. D. Collins (509) 375-2726	Field technique development	Image inspections for metals, wood, composites, plastics, concrete, etc. (e.g., sizing and locating flaws, detection of rebar in concrete, locating buried materials).
6. Micropenetration Indenter	NBS R. S. Polvani (301) 921-2992	Equipment/technique development	Measurement of hardness and other plastic/elastic properties (e.g., on coatings, thin materials).
7. Nondestructive Evaluation Development for Ceramic Materials	ANL W. A. Ellingson (312) 972-5066	Technique development	Ceramics process control and inspection of ceramic structural components (e.g., through material property characterization for ceramics in green state and correlation of detected flaws with fracture in the dense state).
8. Nondestructive Evaluation Development for Light-Water Reactors	ANL D. S. Kupperman (312) 972-5066	Feasibility evaluations, system development and evaluation	Inspection of stainless steel components and weldments through weld overlays; leak detection from piping, vessels, etc.
9. Nondestructive Evaluation for Heat Engine Ceramics	LeRC S. J. Klima (216) 433-6019	Identification and development of NDE techniques	Assessment of degradation and process control applications for ceramics.
10. Nondestructive Evaluation of Acid Rain Damage to Materials	ANL C. A. Youngdahl (312) 972-5066	Overall program, technique evaluation and application	Assessment of damage (corrosion, dissolution, microcracking, etc.) to materials (concrete, brick, mortar, natural stone, paints, metals) due to environmental conditions.
11. Nondestructive Evaluation of Advanced Ceramic Composite Materials	INEL J. B. Walter (208) 526-0033	Experimental evaluations	Ceramics microstructural evaluation.
12. Nondestructive Evaluation of Ceramic Materials	ORNL R. W. McClung (615) 574-4466	Technique and instrument development; signal analysis	Inspection of ceramic materials and ceramic bonds.
13. Nondestructive Evaluation of Graphite Materials	ORNL R. W. McClung (615) 574-4466	Technique and instrument development; signal analysis	Inspection of graphite, graphite composites and other low atomic number materials.

APPENDIX B

RESOURCES AND OPPORTUNITIES IN NDT RESEARCH

APPENDIX B

RESOURCES AND OPPORTUNITIES IN NDT RESEARCH

This appendix assembles information of possible interest to industry; more specifically, it describes some opportunities for industrial interaction with the federal laboratory and academic research communities, focusing primarily (but not exclusively) on NDT R&D. Some sources of information on NDT technology are also presented. Items discussed include:

- DOE-Industry Technology Exchange Research Program (B.1)
- NBS Research Associate Program (B.2)
- DOD Nondestructive Testing Information Analysis Center (B.3)
- DOD Manufacturing Technology Information Analysis Center (B.4)
- Center for Nondestructive Evaluation at Iowa State University (B.5).

Presented here is information most directly related to NDT technology. For information concerning resources on the overall federal scientific and engineering effort, The Directory of Federal Laboratory and Technology Resources 1986-1987 (PB86-100013), prepared by the Center for the Utilization of Federal Technology (CUFT), National Technical Information Service (NTIS), U.S. Department of Commerce, is an appropriate reference. Other products of CUFT/NTIS to promote transfer of federal technology to the U.S. economy includes: monthly NTIS Tech Notes, annual Federal Technology Catalogs, weekly Government Inventions for Licensing Newsletter, and annual Catalogs of Government Patents. Inquiries can be addressed to:

Center for Utilization of Federal Technology
National Technical Information Service
U.S. Department of Commerce
Springfield, VA 22161

Another overall program for technology transfer exists at NASA to disseminate information concerning their activities. The Technology Utilization Program promotes further use of NASA-developed technology through a variety of means including a Technology Application Team (Research Triangle Park, North Carolina), Industrial Applications Centers throughout the United States, and

various publications. Opportunities exist at NASA laboratories for cooperative undertakings with industry. For opportunities in the NDT area, the NDT Section/Division at the laboratory of interest should be contacted directly.

B.1 DOE - INDUSTRY TECHNOLOGY EXCHANGE RESEARCH PROGRAM

The DOE's Office of Energy Research has recently initiated a technology exchange research program intended to improve relations between the laboratories and the private sector and to promote technology transfer from the laboratories to industry.^(a) In its first series of appointments in 1985, visiting research fellowships were awarded to 12 scientists and engineers from private industry at seven DOE laboratories.

Researchers are collaborating with the DOE laboratories in chemical, civil, electrical, and mechanical engineering; physics and biophysics; material science; medical science and technology; and microbiology. Participants are working on individual projects with potential applications for medical diagnostic tools, advanced engines, corrosion resistant materials, and computer simulation. The DOE and the companies share the participants salaries. For more information on the program, contact H. Young at (301) 353-3995.

B.2 NBS RESEARCH ASSOCIATE PROGRAM

The Research Associate Program at NBS enables scientists and engineers from industrial, professional, or trade organizations to work for specified periods (usually 1 to 3 years) at either the Gaithersburg, Maryland or the Boulder, Colorado laboratories.^(b) The Research Associate remains an employee of the sponsoring organization, which pays the Associate's salary, benefits, travel and relocation expenses. NBS furnishes office, laboratory, and professional support.

(a) "DOE Labs Hosting Industry Scientists in New Co-op, Tech Transfer Program," DOE This Month, September 1985.

(b) "Research Associate Program," 6-page leaflet available from the NBS, Office of Research & Technology Applications, Gaithersburg, MD 20899, (301) 921-2226.

The Research Associate Program has been making NBS research and facilities accessible to U.S. industry since the early 1920s. More than 500 organizations and 1500 individuals have participated in the program since its inception.^(a) Presently, there are more than 200 Research Associates at NBS, working in over 55 separate research programs. Approximately six are working in areas related to NDE.

To join the Research Associates Program, one must first submit a plan for a research project that is of clear mutual interest to industry (i.e., the sponsoring organization) and to NBS. Once a mutually acceptable plan is approved, a Memorandum of Agreement is prepared and executed by both parties. The Agreement sets forth the nature, objectives, and scope of the project. It also describes the terms and conditions of the relationship between the sponsor and NBS, including the assignment of patent rights that might arise from the research.^(a)

The NBS Office of Research and Technology Applications (Room A403, Administration Building, NBS, Gaithersburg, Maryland 20899) coordinates the Research Associate Program. They provide information to potential sponsors, arrange meetings between sponsor and appropriate NBS personnel, and help draw up the Memorandum of Agreement.^(a) For general information on the Research Associate Program contact H.E. Sorrows, (301) 921-2226.

Research Associates are currently needed in the following NDE areas: x-ray imaging, contact: J. Motz, (301) 921-2201; ultrasonic inspection of concrete, contact: N. J. Carino, (301) 921-2648; and polymer cure monitoring, contact: F. J. Mopsick, (301) 921-3851.

Industry may also arrange to use certain NBS facilities on a time/cost basis. Among facilities of possible interest to NDE researchers are: the NBS Research Reactor, contact: R. S. Carter, (301) 921-2421; the Metals Processing

(a) "Research Associate Program," 6-page leaflet available from the NBS, Office of Research & Technology Applications, Gaithersburg, MD 20899, (301) 921-2226.

Laboratory, contact: J. R. Manning, (301) 921-3354; and the Automated Manufacturing Research Facility, contact: P. N. Nanzetti, (301) 921-3421.^(a)

Recently, NBS decided to make selected facilities available to U.S. researchers for proprietary work, on a cost-recovery basis.^(a) It is hoped this will increase critical technology transfer from federal laboratories to private industry, and perhaps help increase competitiveness in certain foreign markets. Industries that want additional information on proprietary research opportunities in NDE should contact the Office of NDE directly: H. T. Yolken, Chief or L. Mordfin, Deputy Chief, (301) 921-3331.

B.3 DOD NONDESTRUCTIVE TESTING INFORMATION ANALYSIS CENTER (NTIAC)

The NTIAC is one of about twenty DOD Information Analysis Centers. It provides a range of information services in NDT. Although its primary obligation is to the DOD and DOD contractors, services are also available to other government agencies and the private sector. It is administered by the Defense Logistics Agency and is operated by the Southwest Research Institute of San Antonio, Texas.

The technical scope of NTIAC is the entire field of NDT methodology and instrumentation, materials and components testability data, quality and reliability assessment data, and NDT engineering data. An Information Support System consisting of computerized bibliographic data and index files, together with a corresponding document collection, is the basic information resource of NTIAC.

Services provided by NTIAC include: NTIAC Newsletter (current awareness service available free to interested parties), custom bibliographies, technical inquiries, and special services (e.g., support of technical conferences, commissioned studies). NTIAC also produces a variety of publications including Technology Assessments, Critical Reviews, State-of-the-Art Surveys, Handbooks and Databooks.

(a) "Facilities of the National Bureau of Standards", NBS Special Publication 682, NBS, Washington DC, September 1984.

For more information on NTIAC, contact:

NTIAC
Southwest Research Institute
P.O. Drawer 28510
San Antonio, TX 78284
(512) 684-5111 ext. 2362

B.4 DOD MANUFACTURING TECHNOLOGY INFORMATION ANALYSIS CENTER (MTIAC)

Another DOD Information Analysis Center of possible interest to manufacturing industries is the MTIAC. MTIAC provides services similar to the NTIAC, but in the area of manufacturing technology for defense systems. Specific areas include metals, nonmetals, electronics, CAD/CAM, inspection and test, and munitions. The inspection and test area could be of principal interest to developers and users of NDT technology.

For more information on MTIAC contact:

MTIAC
Case and Company, Inc.
Suite 2109
Prudential Plaza
Chicago, IL 60601
(312) 567-4730

B.5 CENTER FOR NONDESTRUCTIVE EVALUATION AT IOWA STATE UNIVERSITY

The Center for Nondestructive Evaluation at Iowa State University is one of more than 30 University/Industry Cooperative Research Centers established under the National Science Foundation (NSF) University/Industry Cooperative Research Centers Program. The Program, initiated in 1973, stimulates industrial support of university research through centers that create long-term collaboration between the university and industry in research areas of mutual interest. With cofunding from groups of industrial firms, the program initiates university research programs that are compatible with university research objectives and responsive to industry's research needs. NSF support is phased out over five years as industry's support increases and the centers develop along their independent paths determined by the principal investigator, the university policy and objective, and industry requirements. Over 200 companies contributed funds to the centers in 1985.

The Center at Iowa State University, initiated in 1985, is the only one devoted to NDE research. The objectives of the Center for NDE are:

- to pursue research in advanced NDE and materials reliability
- to increase the number of students in graduate degree programs as a consequence of their involvement in NDE research and early contact with industry
- to establish a major focal point for NDE interaction, technology transfer, and technology implementation with industry.

For more information concerning the NSF University/Industry Cooperative Research Program and research centers contact:

F. Betz or A. Schwarzkoff
Industry/University Cooperative
Research Projects Program
National Science Foundation
Washington, D.C. 20550
(202) 357-7784

For information concerning the Center for NOE at Iowa State University contact:

D.O. Thompson
Center for Nondestructive Evaluation
215 Applied Sciences Center
Iowa State University
Ames, IA 50011
(515) 294-8152

DISTRIBUTION

<u>No. of Copies</u>		<u>No. of Copies</u>
<u>OFFSITE</u>		J. E. Doherty Vice President, Research and Engineering Magnaflux Corporation 7300 West Lawrence Avenue Chicago, IL 60656
30	DOE Technical Information Center	
20	J. Demetrops Office of Industrial Programs U.S. Department of Energy 1000 Independence Avenue, S.W. Washington, DC 20585	T. Feiertag MS C 914 Los Alamos National Laboratory Los Alamos, NM 87545
	A. L. Broz U.S. Army Materials Technology Laboratory Arsenal Street Watertown, MA 02172 Attn: SLCMT-MSI-NE	J. Field Administration Manager, Sales and Marketing Gaston County Dyeing Machine Company P.O. Box 308 Stanley, NC 28164
	R. A. Buchanan Manager, NDT Technology Center Organization 93-60, Bldg. 533 Lockheed Missiles and Space Co., Inc. 815 E. Middlefield Road Mountain View, CA 94043	J. Flaherty Magnaflux Corporation 7300 West Lawrence Avenue Chicago, IL 60656
	O. J. Burchett Nondestructive Testing Technology Division 7551 Sandia National Laboratories Albuquerque, NM 87185	R. E. Green, Jr. Johns Hopkins University Center for Nondestructive Evaluation Maryland Hall, Room 102 Baltimore, MD 21218
	R. M. Channey Amoco Oil Company P.O. Box 400 Naperville, IL 60566	L. Gully AFWAL/MLTM Wright Patterson AFB, OH 45433
	D. T. Cooper AFWAL/MLTM Wright Patterson AFB, OH 45433	C. Hellier Hellier Associates, Inc. Essex Plaza P.O. Box 818 Essex, CT 06426

No. of
Copies

J. Heyman
NASA Langley Research Center
Bldg. 1230, Room 135
Hampton, VA 23665

R. Lyons
Technical Manager, Market
Research
United Merchants and
Manufacturers, Inc.
P.O. Box 2148
Greenville, SC 29602

R. C. McClung
Metals and Ceramics Division
Oak Ridge National Laboratory
P.O. Box X
Oak Ridge, TN 37831

J. C. Minter
Garret Turbine Engine Company
P.O. Box 5217
MS93-393/503-4y
Phoenix, AZ 85010

L. Mordfin
National Bureau of Standards
Office of NDE
Washington, DC 20234

J. Moyzis
AFWAL/MLLP
Wright Patterson AFB, OH 45433

E. Papadakis
Ford Motor Company
Manufacturing Development
Center
24500 Glendale Avenue
Detroit, MI 48239

J. Patsey
United States Steel Corporation
Room 1715
600 Ranch Street
Pittsburg, PA 15230

No. of
Copies

G. Pherigo
EPRI NDE Center
1300 Harris Blvd.
Charlotte, NC 28215

R. E. Philleo
7420 Annwood Court
Annandale, VA 22003

K. J. Reimann
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439

M. Savitz
Garret Corporation
9851 Sepulveda Blvd.
Los Angeles, CA 90009

J. A. Seydel
Idaho National Engineering
Laboratory
EG&G, Idaho
P.O. Box 1625
Idaho Falls, ID 83415

W. W. Shurtleff
Nondestructive Testing
Technology Division 7552
Sandia National Laboratories
Albuquerque, NM 87185

R. Streit
University of California
Lawrence Livermore National
Laboratory
P.O. Box 808
Livermore, CA 94550

D. O. Thompson
225 Applied Sciences Center
Ames Laboratory
Iowa State University
Ames, IA 50011

No. of
Copies

C. Valente
Kaiser Center for Technology
P.O. Box 877
Pleasanton, CA 94566

A. Vary
MS 23-3
NASA Lewis Research Center
Cleveland, OH 44135

A. E. Wehrmeister
Babcock & Wilcox Co.
R&D Division
P.O. Box 1165
Lynchburg, VA 24506

No. of
Copies

A. R. Willis
Acceptance Technology Division
Sandia National Laboratories
Livermore, CA 94550

ONSITE

DOE Richland Operations Office

J. J. Sutey

58 Pacific Northwest Laboratory

A. S. Birks (20)
B. L. Mohler
N. L. Moore (5)
G. J. Posakony (20)
S. A. Smith (5)
Publishing Coordination MH (2)
Technical Report Files (5)