NONDESTRUCTIVE TESTING STANDARDS-

A Review

Harold Berger, *editor*

STP 624

ASTM

AMERICAN SOCIETY FOR TESTING AND MATERIALS

NONDESTRUCTIVE TESTING STANDARDS—A REVIEW

A symposium
sponsored by the National Bureau
of Standards, American Society for Testing
and Materials' Committee E-7 on Nondestructive
Testing, and American Society for
Nondestructive Testing
Gaithersburg, Md., 19-21 May 1976

ASTM SPECIAL TECHNICAL PUBLICATION 624
Harold Berger, National Bureau of Standards,
editor

04-624000-22

AMERICAN SOCIETY FOR TESTING AND MATERIALS
1916 Race Street, Philadelphia, Pa. 19103

Library of Congress Catalog Card Number: 76-58567

NOTE

The Society is not responsible, as a body,
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Printed in Baltimore, Md.
June 1977
Second Printing, Baltimore, Md.
September 1984

Foreword

The Symposium on Nondestructive Testing Standards was held at the National Bureau of Standards (NBS) in Gaithersburg, Md., 19-21 May 1976. The meeting was sponsored by NBS, the American Society for Testing and Materials (ASTM), and the American Society for Nondestructive Testing (ASNT). The American National Standards Institute (ANSI) was a cooperating society. The sponsoring committee within ASTM was ASTM Committee E-7 on Nondestructive Testing.

Harold Berger, NBS, served as Chairman of the Symposium Organizing Committee and editor of this publication, and S. D. Hart, Naval Research Laboratory, served as Vice-Chairman. Members of the Symposium Organizing Committee were John Aman, E. I. duPont de Nemours and Co.; R. T. Anderson, ASNT; James Borucki, Magnaflux Corp.; Richard Buckley, Texas Instruments, Inc.; Lance Burgess, ASTM; D. L. Conn, ARMCO Steel Corp.; T. D. Cooper, Air Force Materials Laboratory; E. L. Criscuolo, Naval Surface Weapons Center; Donald Eitzen, NBS; T. J. Flaherty, Detek, Inc.; R. B. Johnson, NBS; Tracy McFarlan, Magnaflux Corp.; R. B. Moyer, Carpenter Technology Corp.; W. C. Plumstead, United States Testing Co.; Jane Wheeler, ASTM; and R. W. Zillman, Steel Founders Society of America.

The papers included in this volume were all presented at the symposium.

The assistance of R. B. Johnson, NBS, and his committee on symposium arrangements, and of Jane Wheeler and her staff at ASTM throughout the publication process, is acknowledged.

The contributions of the session chairmen at the meeting also are acknowledged. R. B. Moyer, John Aman, Richard Buckley, James Borucki, D. L. Conn and Donald Eitzen served as Session Chairmen.

Related ASTM Publications

Acoustic Emission, STP 505 (1972), 04-505000-22

Nondestructive Rapid Identification of Metals and Alloys by Spot Tests, STP 550 (1973), 04-550000-24

Monitoring Structural Integrity by Acoustic Emission, STP 571 (1975), 04-571000-22

Practical Applications of Neutron Radiography and Gaging, STP 586 (1976), 04-586000-22

A Note of Appreciation to Reviewers

This publication is made possible by the authors and, also, the unheralded efforts of the reviewers. This body of technical experts whose dedication, sacrifice of time and effort, and collective wisdom in reviewing the papers must be acknowledged. The quality level of ASTM publications is a direct function of their respected opinions. On behalf of ASTM we acknowledge their contribution with appreciation.

ASTM Committee on Publications

Editorial Staff

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Introduction

Nondestructive testing, the examination of materials in such a way that the intended use of inspected material is not impaired, is used widely in industry. Techniques commonly applied include radiographic, magnetic particle, liquid penetrant, ultrasonic acoustic, eddy current, leak testing, and visual optical. These methods provide information about material properties and about the location and type of discontinuities that may be present in a material or system. The test information is used to assess the performance or reliability of the material or system.

The use of nondestructive testing in industry depends on standards. Standards are used to compare results, to calibrate equipment, to assure uniform, reproducible results, and to help determine what is acceptable and what is not.

Standards for nondestructive testing were pioneered in the 1920s by the U.S. Army and Navy. As of 1973, there were 39 military specifications and standards dealing with nondestructive testing. ASTM Committee E-7 on Nondestructive Testing was formed in 1938. There are 47 nondestructive testing standards in the *1975 Annual Book of ASTM Standards* and a large number of new nondestructive testing documents in preparation. Other organizations, such as the American Society for Nondestructive Testing (ASNT), the American Society of Mechanical Engineers (ASME), and a number of government bodies also are involved in standards, codes, and personnel certification procedures for nondestructive testing.

One of the driving forces for this symposium was the realization that there are a large number of standards for nondestructive testing, that they originate in several organizations, and that the standards have evolved over a period of years. There also were indications from a number of users of nondestructive testing that the present system of standards does not satisfy all requirements. There was some lack of reproducibility and there were omissions in some areas, for example, ultrasonic transducer calibration procedures or methods of assessing radiographic resolution.

For all these reasons and because increasing demands were being made on nondestructive testing, for example, to provide more quantitative results so fracture mechanics criteria could be used in design, this seemed like a good time to step back and examine nondestructive testing standards. The symposium was organized to perform that examination by looking at nondestructive testing standards in a broad way. Where are standards unsatisfactory or lacking? What suggestions can be made for improvement?

The symposium addressed these questions in 38 papers presented over three days in six sessions. Most of these papers are contained in this publication. It is the hope of the symposium organizing committee and the symposium sponsors that these papers will inspire further thought on nondestructive testing standards and help to bring forth ideas for improving these standards and the measurements made from them.

Harold Berger
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R. W. McClung[1]

ASTM Nondestructive Testing Standards Program*

REFERENCE: McClung, R. W., "**ASTM Nondestructive Testing Standards Program,**" *Nondestructive Testing Standards—A Review, ASTM STP 624,* Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 3–11.

ABSTRACT: The American Society for Testing and Materials' (ASTM) program for developing nondestructive testing (NDT) standards resides primarily in Committee E-7 on Nondestructive Testing. To meet this responsibility, Committee E-7 is subdivided functionally into subcommittees representing most of the major methods of NDT. The many activities necessary to the development of standard documentation that are conducted include industry surveys to determine interest, needs, and practices, performance of experimental studies through extensive cooperative studies in both government and private organizations, document preparation, and interlaboratory testing. Committee E-7 is responsive to requests from other ASTM committees as well as other standard organizations (for example, American Society of Mechanical Engineers). Although benefits to industry have accrued in the consensus standards, significant improvements are needed to provide more relevant, quantitative, reproducible results.

KEY WORDS: standards, quality control, technical writing, nondestructive tests

The American Society for Testing and Materials (ASTM) was formed for the development of standards on characteristics and performance of materials, products, systems, and services. In this context, the term "standard" refers to documents including test methods, definitions, recommended practices, classifications, and specifications. The mechanism through which these standards are developed is that of over 100 separate committees with primary interests in specific materials, products, or disciplines. Since participation in the respective committees is voluntary, and concerted effort is made to obtain a broad industry-wide involvement and agreement, the resultant standards may be used to represent true consensus

*Research was sponsored by the Energy Research and Development Administration under contract with the Union Carbide Corporation.

[1]Group leader, NDT Development, Metals and Ceramics Division, Oak Ridge National Laboratory, Oak Ridge, Tenn. 37830.

documents. The consensus is enhanced by joint participation of producers, consumers, and other interested parties. An important committee in the Society is ASTM Committee E-7 on Nondestructive Testing,[2] which was organized in 1938 and has a current (as of Jan. 1976) working membership of over 225.

It must be recognized that the generic term, "standard," is used also in ways other than documents, for example, to denote tangible items of hardware that may be identified as "reference standards," "calibration standards," "acceptance standards," or other similar nomenclature. These devices may be manufactured specially or may be selected items from a batch of a manufactured product. Their functions vary in nondestructive testing (NDT) and may include providing: (*a*) assistance in establishing the proper operating parameters for an examination, (*b*) continued or recurrent assurance that an examination is proceeding in the intended manner, (*c*) a benchmark of response for comparison with that from inspected products, and (*d*) a positive go-no-go indication of acceptance or rejection of material. Many of the subsequent papers in this book will provide detailed discussions of these various types of hardware standards. Therefore little more will be said about them in this paper, except as it may be necessary to show that their development or description is an integral part of the process of preparing standard documents. This paper will concentrate on the organization for producing NDT standards, the determination of needs for standards, and the mechanism for establishing ASTM concensus standards for NDT.

Organization of ASTM Committee E-7

For efficient fulfillment of its responsibility, ASTM Committee E-7 is subdivided functionally into numerous administrative and technical subcommittees. The first discussion and emphasis will be on the technical subcommittees, since they have originated and prepared all the technical standards of ASTM Committee E-7.

Technical Subcommittees

The functional division of the work of ASTM Committee E-7 has caused most of the technical subcommittees to be identified with and responsible for specific disciplines of NDT. The following list, without supplementary comments, should be sufficient to identify the scope of activity and type of documentation prepared by each group. The decimal system of identification used by ASTM identifies both the committee and subcommittee and even further subdivisions.

[2]Turner, R. E., *Nondestructive Testing*, Vol. 4, No. 4, Aug. 1971, pp. 251-253.

Subcommittee	Activity
E07.01	Radiographic Practice and Penetrameters
E07.02	Reference Radiographs
E07.03	Magnetic Particle and Liquid Penetrant Testing
E07.04	Acoustic Emission
E07.05	Neutron Radiography
E07.06	Ultrasonic Testing Procedure
E07.07	Electromagnetic Methods
E07.08	Leak Testing
E07.09	Materials Inspection and Testing Laboratories

Administrative Subcommittees

In addition to these technical subcommittees, there are several administrative subcommittees that centralize various activities primarily (but not exclusively) in support of the overall committee and its respective technical subcommittees. Since the function is not to produce standard documentation within a readily identifiable technical discipline, perhaps a few words of explanation will be in order for the administrative subcommittees.

Subcommittee E07.90 is the Executive Council that serves as the steering committee for general business matters such as approval of new members, establishment of new work scopes, planning for symposia, and other *ad hoc* business items.

Subcommittee E07.91 is the USA Committee for International Standards Organization/Technical Committee 135 on NDT. This subcommittee coordinates and provides the technical participation of the United States in the cited international organization.

Subcommittee E07.92 on Editorial Review provides editorial support to all the technical subcommittees.

Subcommittee E07.93 on Illustration Monitoring assists ASTM headquarters in reviewing the production of reference radiographs and other illustrations that are integral parts of Committee E-7 standards.

Subcommittee E07.96 on Awards coordinates all activities relative to Society and Committee awards to both students and members.

Subcommittee E07.98 on New Methods Review maintains an active awareness of all nondestructive testing methods not covered currently by standardization activity and makes recommendations when standards in additional methods appear to be necessary.

Subcommittee E07.99 on Liaison coordinates all liaison activities with other ASTM committees as well as other technical organizations.

Sections and Task Groups

Because of the broad scope of activities within each of the technical subcommittees, it has been necessary to provide further subdivisions. Permanent subdivisions for work having a continuing interest are called sections; subdivisions with only temporary status until a specific task is accomplished are designated as Task Groups. The latter, which may be a subdivision of the committee, a subcommittee, or a section, can have a life span exceeding a year. Within the nine technical subcommittees there are well over 50 active sections and an unknown number of task groups. Although it is not considered necessary in this paper to identify each of the sections, for illustration, the sections in Subcommittee E07.06 on Ultrasonic Testing cover the following activities: glossary, aluminum reference blocks, contact testing, thickness testing, testing of welds, immersed testing, angle-beam-contact testing, flaw-size determination, equipment standardization, steel reference blocks, pipe and tubing, material properties, and testing of castings. The other technical subcommittees are organized similarly with an appropriate number of sections to function in the various activities that would be pertinent to the subcommittee and its method of NDT.

Determination of Needs for Standards

What motivates the generation of a new standard? What motivates this large organization that has been described? Recognition of the need for a new (or improved) standard can (and has) come through many channels. Probably the most frequent sources are the technical experts within the subcommittee structures who recognize both the need and the mechanism for satisfying the need. But numerous other sources (and requesters) for specific standards include other ASTM technical committees, other technical organizations and societies (who use or want to use ASTM Committee E-7 documents), government agencies, and private industry. Obviously, not every request represents a genuine need for an industry-wide consensus standard such as prepared by ASTM Committee E-7. Therefore, all requests must be screened and evaluated (perhaps with formal or informal industry surveys) to determine the need (or practicality) of preparing the requested standard. If an affirmative decision is reached, the stage is then set for another addition to the ASTM Committee E-7 family of standards.

Development of a Standard

After a decision is made to develop a new standard, what is the mechanism for its preparation and approval? The first obvious requirement is to establish where in the organization that the preparation will be performed.

For most standards, with the initiating force originating within a subcommittee (or section), the preparation most probably will be within the same organization. However, for requests external to the committee, decisions must be made at the committee or executive council level about the most appropriate subcommittee depending upon the technical requirements of the documentation. In turn, the subcommittee determines the proper section for the activity. On occasion it may be necessary to establish a new section within a subcommittee or (less frequently) a new subcommittee to deal with a new endeavor. The actual preparation of the first draft of the proposed document normally will be done by a small task group of individuals with the necessary expertise and interest in the new standard. On occasion it may be necessary to recruit additional workers with desired experience and interest. For example, external requesters are encouraged to provide technical participation and to be involved in preparing the documents of interest to them. The input for the draft document is derived not only from the personal knowledge and technical awareness of the task group members but also may include information derived from (*a*) standards previously prepared by industry, government, or other organizations, (*b*) technical surveys, (*c*) experimental work, (*d*) interlaboratory tests, or other sources. After a new draft standard has been prepared and has achieved consensus agreement (but not necessarily unanimity) at the task group or section level, it is ready for balloting within the parent subcommittee. With subcommittee approval, a letter ballot and copy of the draft is sent to each voting member of the subcommittee. For a valid ballot, at least 60 percent of the members must respond by voting (*a*) affirmatively (with or without comments on any portion of the draft), (*b*) negatively (comments of technical justification are required), or (*c*) an abstention. Upon completion of the balloting, the comments and negative votes (if any) are considered by the drafting group, and usually adjustments will be made to the documents to accommodate the wishes of those having objections. If the changes are deemed to be technical in nature, the subcommittee balloting process must be repeated. After a successful subcommittee ballot (with any changes in the draft being only editorial), the draft is ready for a letter ballot of the entire committee. The voting requirements are the same as for the subcommittee ballot. Technical change to the content of the document requires reballoting by the subcommittee. Again it should be noted that unanimity is not mandatory. However, if a negative vote is not resolved by documentary changes and is considered to be nonpersuasive by the other members of the subcommittee or committee (depending on the ballot level), positive action to advance the standard must be recorded and reported to ASTM headquarters. (Only rarely has it been necessary to take such action. Almost every document has attained unanimous concurrence.)

After an acceptable committee ballot including all modifications, the proposed standard is sent to ASTM headquarters for a Society ballot through the pages of *ASTM Standardization News*. Unless there is a rare case of a new, previously unconsidered, technical reason for a negative vote from some Society member, the document is adopted as a standard and is printed in the next edition of the *Annual Book of ASTM Standards* (currently in Part 11). A valid negative vote, if technical change in the document is required, of course, will require a repetition of the entire balloting process.

All of these steps demonstrate that the products are truly consensus standards with adequate opportunity to receive and consider many viewpoints.

What is It?

Thus far our discussion has emphasized the organization and the mechanism for producing standards without consideration of the type of standard (other than the distinction implied by the NDT methods of interest noted in the subcommittee structure). As one of the committees of ASTM dealing with methods of testing, the accepted range of activities includes those standards that would be necessary or useful for the performance and evaluation of a nondestructive test. This would include such documents as a glossary to establish a standardized nomenclature and language, standards related to materials and components needed during a nondestructive test, recommended practices, methods, or guidelines for performing nondestructive tests in a standard manner, and educational documents to provide additional information about NDT. Perhaps further explanation or examples are in order to assure understanding of the foregoing. Among the ASTM standards that are prepared specifically to deal with NDT materials and components are such documents as Controlling Quality of Radiographic Testing (E 142), Recommended Practice for Fabricating and Checking Aluminum Alloy Ultrasonic Standard Reference Books (E 127), and Recommended Practice for Evaluating Performance Characteristics of Pulse-Echo Ultrasonic Testing Systems (E 317). (Other parallel documents may be found in the Table of Contents and body of Part 11 of the *Annual Book of ASTM Standards*.) It may be noted that some of these standards are dedicated to the description and discussion of some of the hardware standards that were mentioned earlier in the paper. Among the ASTM standards on recommended methods or practices for performing an NDT examination may be found Dry Powder Magnetic Particle Inspection (E 109), Recommended Practice for Standardizing Equipment for Electromagnetic Testing of Seamless Aluminum-Alloy Tube (E 215), or Tests for Leaks Using the Mass Spectrometer Leak Detector in the Inside-Out Testing Mode (E 493). This type of standard usually (but not always) will contain descriptions and discussions about the use of various types of hardware standards that are recommended to be used to assure a standardized performance. Recommended Practice for Liquid Penetrant Inspection Method (E 165) is an example of an educational document that describes several techniques and materials and provides guidelines to their use.

Having discussed the types of standards that are written by ASTM Committee E-7, it is appropriate to cite an area of exclusion. Specifications that establish acceptance-rejection criteria for products are not within the jurisdiction of ASTM Committee E-7, but are reserved for the product committees. However, even in this restricted zone, ASTM Committee E-7 can and does provide useful services in many ways, for example, the many E-7 documents can be (and are) referenced in the product committee documents to establish the standard methods of examining the product. To this the product committee simply has to add the acceptance (or rejection) level based on the finding or NDT response. As an aid to accomplish this, some of the NDT standards provide for several levels of response for comparison purposes from which a rejection level may be set. Among several examples that could be cited are the several standards of reference radiographs containing various levels of severity of common discontinuities in different kinds of castings and welds. Beyond the supplying of technical documents for referencing, ASTM Committee E-7 by mutual agreement, can work directly (through joint working groups, common memberships, or official liaison) with other committees or organizations to produce acceptance specifications that are administered under the product committees (or other organizations).

Care and Keeping of Standards

The successful working of the described activities has produced the 47 standards that are listed in the *1975 Annual Book of ASTM Standards*; several more standards have been approved since the printing date, and a large number of new documents are in various stages of preparation. But what happens after a standard has been approved and printed? A significant amount of effort is expended toward monitoring and updating the documents to assure their continued relevancy. The impetus for changes may begin as early as receipt of comments during final balloting of the initial document, or it may arise from (*a*) comments received from initial users, (*b*) technological changes, or (*c*) a recognition by committee members that improvements are needed. Need for change may be recognized during the mandatory five-year review, at which time the document must be reapproved, revised (both with letter ballots), or it will be deleted automatically. With these activities the documents should not be dormant, obsolete, or unusable.

Conclusions and Recommendations

The ASTM standards program as discussed through Committee E-7 is a successful working arrangement for producing needed consensus standards for NDT that are used throughout industry. There is justifiable pride in the many contributions that have been made to the industrial community through the many standards and the research and development that has been accomplished to establish the technological base for the standards. But, like almost everything else, there is room for improvement. The recommendations to follow will include items internal and external to the committee. Although detailed or amplified discussion will not be provided (nor is the listing considered to be exhaustive), the following areas of improvement in the opinion of the author, would impact the usefulness of the ASTM NDT standards significantly.

1. Strive to provide more specific detail wherever practical as an aid toward achieving more reproducible results. (A complaint occasionally to frequently heard is that some of the standards are so general as to be innocuous and useless.)

2. Shorten the time interval between initiation and publication of a standard. (Occasionally on complex or controversial documents, the reaching of a useful consensus and possible reballoting can stretch the time before completion. But much of the delay can be laid to our own inefficiencies and procrastination, not to the system. Statements about how long a time was required before a certain document became published point the finger at ourselves, not others. Of course, we recognize that ASTM is a voluntary organization, and most of our members are hard working contributors for whom their Committee E-7 activities are extracurricular as a "labor of love." Therefore, the employers' needs have higher priority and occasionally (or frequently) conflict. The solutions to the glib statement, "shorten the timetable," are manifold and should be explored and implemented, but one should be a result of the next recommendation.)

3. Actively seek more industry and government participation in ASTM Committee E-7 standards. (This would include making employers more aware of the benefits in preparing and using ASTM standards to enhance management support and encouragement of their technical experts to participate in the standardization activities in a timely manner. Success not only should mean shortened timetables but also broader imput to make standards even more technically relevant (and used).)

4. Get more coordination and participation with other standards-writing groups. (This includes other ASTM committees as well as other societies and organizations. Too often there is a proliferation of committees and activities preparing NDT documents. This leads at best to redundant work and, at worst, to contradictory recommendations and requirements and,

on occasion, obsolete or inaccurate standards due to an inadequate base of expertise. There needs to be more standardization of NDT standards. ASTM offers a system for achieving technically valid, consensus standards to meet any requirements.)

5. Be prompt in responding to requests for assistance or in recognizing needs for new or improved standards. (This is a necessary adjunct to the previous recommendation for minimizing the number of parallel or competing standards activities. However an unrequited need encourages proliferation and could lead to accusations of a lack of professional responsibility.)

6. Be sure of the technical facts in the standards. (The other papers in this symposium will deal in detail with the needs and recommendations on this subject and does not need further discussion here.)

ASTM Committee E-7 is recognized internationally as one of the leading organizations for NDT standards. With appropriate implementation of these and other improvements, we can play an even greater role in assuring that the best current technology is known, understood, and applied.

Israel Resnick[1]

International Nondestructive Testing Standards

REFERENCE: Resnick, Israel, "**International Nondestructive Testing Standards,**" *Nondestructive Testing Standards—A Review, ASTM STP 624*, Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 12–21.

ABSTRACT: The International Organization for Standardization (ISO) and its objectives are described. ISO Technical Committee (TC) 135 on Nondestructive Testing is the committee responsible for developing nondestructive testing (NDT) standards. The American National Standards Institute (ANSI) is the United States member body of ISO. Its activities and organization are explained. The scope and structure of ISO/TC 135 is reviewed, as well as its liaison with a number of other TCs and international organizations having an interest in NDT standards. The United States participates in ISO/TC 135 through the activities of its Technical Advisory Group (TAG) for ISO/TC 135 which also is ASTM Subcommittee E07.91, USA Committee for ISO TC/135, of ASTM Committee E-7 on Nondestructive Testing. Its representation, organization, operating procedures, and activities are reviewed. The steps for developing an ISO standard from the draft document in the working group through its approval by ISO Council is covered. The present status of ISO international standards, draft ISO standards, and draft proposals in the NDT area are provided. The importance of international standards and their effect on trade and related activities is covered briefly.

KEY WORDS: nondestructive tests, standards, international relations

International Organization for Standardization

The International Organization for Standardization (ISO) is the international specialized agency for standardization. Its objectives is worldwide agreement on international standards with a view to the expansion of trade, the improvement of quality, the increase of productivity, and the lowering of costs. The work of ISO involves the development of international standards in virtually every area of technology, except for electrotechnical standards which are the responsibility of the International Electrotechnical Commission (IEC), an affiliate of ISO.

[1] Program administrator, American National Standards Institute, New York, N.Y. 10018.

In 1975, the ISO membership consisted of the national standards bodies of 63 countries, with 18 additional correspondent members. A correspondent member is normally an organization in a developing country. A member body of ISO is the national body "most representative of standardization in its country." Although ISO is a nongovermental organization, more than 70 percent of the ISO member bodies are either governmental institutions or organizations incorporated by public law.

Technical Work

The technical work of ISO is carried out through technical committees (TC). The secretariats of the technical committees are assigned among the member countries. The scope of each committee is approved by the ISO Council. Within this scope, the committee determines its own program of work. The technical committee, in turn, may create subcommittees (SC) and working groups (WG) to perform different aspects of the work. A working group is composed of individual experts and not national delegates. At the end of 1975, ISO had in existence 152 technical committees, 492 subcommittees, and 985 working groups.

American National Standards Institute

The United States is represented in ISO by the American National Standards Institute (ANSI). It is the clearinghouse and coordinating agency for voluntary standardization in the United States and is involved in domestic and international standardization activities. On the domestic level, it approves a standard when it has received evidence that all parties having a substantial interest in the scope and provisions of a particular standard have been given an opportunity to participate in the standard's development or to comment on its provisions. ANSI also represents U. S. interests in international standardization work carried out by such nontreaty organizations as ISO, IEC, and Pacific Area Standards Congress (PASC).

ANSI is a nonprofit corporation consisting of a federation of trade, technical, professional, labor, and consumer organizations (organizational members) and industrial and commercial firms (company members). In addition, government agencies and their representatives participate in domestic and international standardization activities.

ISO/TC 135 on Nondestructive Testing

One of the areas of international standardization activity is ISO/TC 135 on Nondestructive Testing. The scope of ISO/TC 135 is "Standardization covering nondestructive testing as applied generally to constructional materials, components and assemblies, but excluding quality levels, by means of: (*a*) glossary of terms, (*b*) methods of test, and (*c*) performance specifications for testing equipment and ancillary apparatus, other than specifications for electrical equipment and apparatus which fall within the range of IEC Committees."

In order to develop nondestructive testing (NDT) standards, ISO/TC 135 was organized into 7 subcommittees, which are listed in Table 1. Also shown is the acronym for the secretariat of each subcommittee. Two of the subcommittees are divided further into working groups. When ISO/TC 135 was created in 1970, its secretariat originally was assigned to the British Standards Institute (BSI). In 1974, the secretariat was accepted by ANSI and reassigned to the United States.

At the present time, ISO/TC 135 has a membership of 41 countries consisting of 21 as "P" (or participating) members and 20 as "O" (or observer) members. In addition, it has established liaison with 17 other ISO committees (internal liaison) and with 8 other international organizations which are interested in NDT activities. A list of these committees and international organizations maintaining liaison is given in Tables 2 and 3, respectively.

United States Participation in ISO/TC 135

Participation by the United States in the activities of ISO/TC 135 is organized through the U.S. Technical Advisory Group (TAG) for ISO/TC 135. This group or TAG also is a subcommittee of the American Society for Testing and Materials (ASTM) (Committee E07.91, USA Committee for ISO TC/135). Its membership consists of representatives of ASTM and other U.S. organizations having an interest in NDT activities such as American Society for Nondestructive Testing (ASNT), American Society of Mechanical Engineers (ASME), and Steel Founders Society of America (SFSA), as well as representatives of government agencies such as the National Bureau of Standards (NBS), the U.S. Army, and the U.S. Navy.

The operating procedures of ANSI state that all organizations having concern and competence in international standards for nondestructive testing and who wish to participate are eligible to have representatives of this TAG. ASTM also has the responsibility of acting as administrator of the USA TAG for ISO/TC 135. The principal function of the TAG is to establish the U. S. position on ISO matters and documents within the scope of ISO/TC 135. In most cases decisions are reached by mail ballot or at meetings which are held two to three times a year. Under exceptional circumstances, when time limitations may not permit a formal canvass, the chairman may make an informed decision as to the U. S. position relative to any question before the TAG.

TABLE 1—*Subcommittees of ISO/TC 135.*

	Nondestructive Testing	Secretariat, ANSI
Standardization covering nondestructive testing as applied generally to constructional materials, components, and assemblies, but excluding quality levels, by means of: (*a*) Glossary of terms, (*b*) Methods of test, and (*c*) Performance specifications for testing equipment and ancillary apparatus, other than specifications for electrical equipment and apparatus which fall within the range of IEC Committees.		
WG 1	Coordination	ANSI
SC 1	Terminology	AFNOR
SC 2	Surface methods	. . .
SC 3	Acoustical methods	ANSI
WG 1	Test system	ANSI
WG 2	Test method	DIN
WG 3	Presentation of results	SIS
SC 4	Electrical and magnetic methods	UNI
SC 5	Radiation methods	DIN
WG 1	Basic rules	DIN
WG 2	Classification of films	DIN
SC 6	Leak detection methods	AFNOR
SC 7	Personnel qualification	ANSI

NOTE—
AFNOR—Association Francaise de Normalisation
DIN—Deutsches Institut für Normung
SIS—Sveriges Standardiseringskommission
UNI—Ente Nazionale Italiano di Unificazione (Italy)

In the case of the TAG for ISO/TC 135, its members also have another important responsibility. They provide advice and technical input concerning the operation of secretariat activities. ANSI is responsible for the operation of the secretatiat of ISO/TC 135/SC 3 on Acoustical Methods and SC 7 on Personnel Qualification. ANSI in turn has assigned the responsibility for conducting the SC 3 secretariat activities to ASTM and the SC 7 secretariat activities to ASNT. The TAG also establishes the U.S. position concerning agenda items for international meetings and has the responsibility for selecting delegates to represent the United States at international meetings of the technical committee, its subcommittees, and working groups.

Development of ISO Standards

The development of ISO standards usually begins at the working group level. An ISO WG is set up by the technical committee or subcommittee

TABLE 2—*ISO TCs in liaison with ISO/TC 135.*

ISO/TC	Title	Secretariat
11	Boilers and Pressure Vessels	ANSI (USA)
17	Steel	BSI (UK)
20	Aircraft and Space Vehicles	BSI (UK)
25	Cast Iron	BSI (UK)
26	Copper and Copper Alloys	DIN (Germany)
42	Photography	ANSI (USA)
44	Welding	AFNOR (France)
58	Gas Cylinders	BSI (UK)
61	Plastics	ANSI (USA)
67	Materials and Equipment for Petroleum and Natural Gas Industries	IRS (Romania)
79	Light Metals and Alloys	AFNOR (France)
85	Nuclear Energy	ANSI (USA)
107	Metallic and Other Nonorganic Coatings	UNI (Italy)
112	Vacuum Technology	BSI (UK)
119	Powder Metallurgical Materials and Products	SIS (Sweden)
155	Nickel and Nickel Alloys	SCC (Canada)
158	Gas Analysis	AFNOR (France)

NOTE—
IRS—Institutul Roman de Standardizare
SCC—Standards Council of Canada

TABLE 3—*ISO/TC 135—NDT liaison with other international organizations.*

Abbreviation	Name of International Organizations
CMEA	Council for Mutual Economic Assistance
CCE	Commission of the European Communities
ICNDT	International Conference for Nondestructive Testing
IEC	International Electrotechnical Commission
IAEA	International Atomic Energy Agency
IIW (IIS)	International Institute of Welding
RILEM	International Union of Testing and Research Laboratories for Materials and Structures

and comprises a restricted number of individually named specialists nominated by P members. Their objective is to develop one or more drafts of standards within the WG scope. Each working group has a leader or convenor appointed by the parent committee to which he reports. The working group convenor, with the help of a secretariat is responsible for the proper conduct of the work. The documents used in the development of an ISO draft document usually are national standards together with related data or other national and international standards which are available. Most of the work is done by correspondence. Members of working groups may correspond directly with each other and the convenor, since as working group members these experts are not national delegates and can work informally. However, the convenor may convene meetings of the working group if questions cannot be resolved by correspondence.

When the working group had developed a working draft that is sufficiently complete, a draft proposal (DP) is prepared. This document represents the decision reached by a majority of the working group either at a meeting or by mail ballot. A copy of this draft is submitted to the ISO Central Secretariat for registration as a draft proposal. The Central Secretariat allocates a number to the draft proposal which will remain the same throughout the development stages of the document and for the published international standard.

Draft Proposal

The draft proposal (preferably in both English and French texts) is circulated by the secretariat of the subcommittee or technical committee for review and voting by the P members and for information to O members and liaison organizations. Together with the draft proposal, the secretariat distributes an explanatory report or introductory note which provides pertinent information concerning the development of the document. This may include documents used as a basis by the working group, reference to data of test results, and information obtained in liaison with other interested committees or international organizations. In most cases the consideration of a draft proposal is dealt with via correspondence, but it may be discussed at a meeting. The voting period for a first draft proposal is approximately three months. After the close of voting, the secretariat distributes a summary of the voting results together with all comments. The secretariat also will distribute a report indicating the action taken as a result of the comments received, and, if necessary, will distribute a further draft proposal. The secretariat decides whether to consider resolution of the comments. If necessary, consideration of successive draft proposals is continued until substantial support of the P members of the technical committees has been obtained. When this point has been reached the document is ready for submittal as a draft international standard.

Draft International Standard

The final text of the approved draft proposal (including the approved changes, if any) is sent to the ISO Central Secretariat for registration and distribution as a draft international standard (DIS). The English and French texts then are reviewed and circulated by the Central Secretariat to all members for approval within six months. Copies also are sent to all technical committees and international organizations in liaison with the originating technical committee. If the draft international standard has been adopted by a majority of the P members and has been approved by 75 percent of the members bodies voting, it can progress further. Otherwise, a revised draft may be prepared for further ballot and approval.

After approval by the member bodies, the technical committee secretariat decides if the comments concerning the document should be resolved by correspondence or at a meeting. Subsequently, the technical committee secretariat prepares a report indicating the action taken on the technical and other major comments made by member bodies (or interested international organizations) and if any objections have not been met, a statement of the reasons. This information, together with the revised text of the draft and related documents, is sent to the ISO Central Secretariat for submittal and acceptance by the ISO Council. When approved by the ISO Council as an International Standard, the document is published in French and English texts.

Status of ISO Documents on NDT

At present, we have three ISO international standards developed by ISO/TC 135. These are

ISO 3057-1974 NDT—Metallographic Replica Techniques of Surface Examination

ISO 3058-1974 NDT—Aids to Visual Inspection—Selection of Low-Power Magnifiers

ISO 3059-1974 NDT—Method for Indirect Assessment of Black Light Sources

In addition we have groups of documents at various stages of development. The following two documents have been balloted as draft international standards and the comments are to be resolved.

DIS 3452 NDT—Penetrant Method for Detection of Surface Discontinuities (21 member bodies approved (5 with comments), 0 disapproved, 0 abstained)

DIS 3453 NDT—Penetrant Inspection—Means of Verification (23 member bodies approved (5 with comments), 1 disapproved (Austria), 1 abstained)

Seven draft proposals in English and French texts recently have been distributed for review and ballot by the members of ISO/TC 135. The completed ballots and comments for the following are to be returned to the ISO/TC 135 Secretariat by 1 July 1976.

DP 5586 NDT—Practices for Checking Leak Tightness by means of a Vacuum Chamber (6.6)[2]

[2] Item numbers refer to work items listed in the Program of Work of ISO/TC 135.

DP 5587 NDT—Locating of Leaks by Means of Compressed Air (6.7)
DP 5588 NDT—Testing for Leak Tightness by Means of Helium—Part III—Locating of Leaks by Means of a Jet of Helium (6.8)
DP 5589 NDT—Testing for Leak Tightness by Means of Helium—Part IV—Locating of Leaks by Means of Compressed Helium—Suction Cup Method (6.9)
DP 5590 NDT—Testing for Leak Tightness by Accumulation and Sniffing of Gas (6.10)
DP 5591 NDT—Locating of Leaks by Means of Ammonia by Overall Pressurization (6.11)
DP 5592 NDT—Locating of Leaks by Means of Ammonia—Suction Cup Method (6.12)

The following draft proposals have been registered by the ISO Central Secretariat. Drafts are being studied or being prepared for ballot at the subcommittee level.

DP 5576 Terminology—Industrial Radiography (1.1)
DP 5577 Terminology—Ultrasonics (1.2)
DP 5578 Magnetization Equipment for Magnetic Particle Inspection (4.2)
DP 5579 Basic Rules for Radiographic Examination of Metallic Materials by X- and Gamma Rays (5.1)
DP 5580 Specification for Radiograph Illuminators (5.2)
DP 5581 Recommended Factors for Testing by Impregnation with Helium (6.1)
DP 5582 Testing for Leak Tightness Using Helium—Part I—Global Methods in a Vacuum (6.2)
DP 5583 Testing for Leak Tightness Using Helium—Part II—Partial Global Method (in a Pocket) (6.3)
DP 5584 Helium Testing in a Vacuum with Accumulation (6.4)
DP 5585 Location of Leak Areas Using Radioactive Tracers (Liquid or Gas) (6.5)

Other items of work which are being studied by the subcommittees and working groups have not yet reached the stage where drafts can be registered for ballot.

It should be noted that ISO standards relating to NDT have been prepared or may be in the process of preparation by other ISO Committees. Such documents pertain to specific areas of their work. For example, ISO/TC 44 on Welding has issued seven ISO standards and recommendations relating to NDT. Typical examples are

ISO/R 947-1969 Recommended Practice for Radiographic Inspection of Circumferential Fusion Welded Butt Joints in

	Steel Pipes up to 50 mm (2 in) Wall Thickness
ISO 2400-1972	Welds in Steel—Reference Block for the Calibration of Equipment for Ultrasonic Examination

Another example is ISO/TC 17 on Steel. Its SC 2 on Steel casting has a working group which will discuss the third draft proposal for an international standard for "Ultrasonic Inspection of Steel Castings" at its next meeting in June 1976. Other international organizations such as the International Institute of Welding (IIW) also have been involved in the development of international standards. As mentioned previously in referring to liaison activities, effective liaison between ISO/TC 135 and other committees and international organizations will help minimize duplication of unnecessary work in standards development.

International Meetings of ISO

The ISO Directives, in Par. 4.4.1, state that "technical committees, subcommittees, and working groups should work as much as possible by correspondence." However, our experience has demonstrated the necessity of holding meetings. In April 1975, ISO/TC 135 held its 2nd Plenary Meeting in Phildelphia. At this meeting the creation of SC 7 on Personnel Qualifications was approved. As mentioned previously, the secretariat of this subcommittee is held by the United States and administered by ASNT. Concurrently with the 1975 TC meeting, SC 3 on Acoustical Methods held its first meeting where it reviewed its program of work and established three working groups to carry out this work. In October 1975, SC 1 on Terminology and SC 5 on Radiation Methods met in Berlin to discuss drafts of documents relating to items of their work.

Significance of International Standards

Americans having an interest in foreign trade are aware of many of the obstacles to doing business overseas. These include problems relating to tariffs, import quotas, freight rates, and financial impediments. However, one barrier to foreign trade that is not always obvious is the problem of foreign, national, and international standards that have become nontariff barriers to trade. International standards that meet with U. S. approval provide a means for U. S. participation in international trade. ANSI actions to strengthen international programs have been taken in recognition of the growing importance of international standards to world trade and world metrication. Because these standards are adopted by many other countries as the bases of product inspection, product approval, and certification systems, they tend to govern product acceptance throughout the world. If U. S. industry does not meet them, it faces competitive disadvantages in marketing its products or services. Therefore, it is essential that the United States participate in their development to ensure that they incorporate the viewpoints of U. S. interests and recognize sound U. S. standards and engineering practices.

As mentioned previously, two major nongovernmental groups are responsible for coordinating and approving a large part of the voluntary international standards in use throughout the world, the ISO, and IEC. ANSI, with the support of its federated memberships, provides the management leadership, coordination, and the financial and administrative support for effective participation in these organizations.

R. W. Zillmann[1]

Nondestructive Testing Standards in the *ASME Boiler and Pressure Vessel Code*

REFERENCE: Zillmann, R. W., "**Nondestructive Testing Standards in the ASME** ***Boiler and Pressure Vessel Code,***" *Nondestructive Testing Standards—A Review, ASTM STP 624,* Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 22-29.

ABSTRACT: Nondestructive testing (NDT) constitutes an important part of the *ASME Boiler and Pressure Vessel Code.* Section V deals exclusively with nondestructive examination (NDE). This paper is a general description of all NDE methods referenced in the *ASME Boiler and Pressure Vessel Code,* the origin of specific standards documented in other societies, adaptation, and modification of these standards to meet *ASME Boiler and Pressure Vessel Code* requirements, and selection of acceptance criteria by other sections of this Code. The mechanism for implementing revisions in order to keep abreast of technological advances is described briefly and assessed.

KEY WORDS: nondestructive tests, standards, coding theory

The American Society of Mechanical Engineers (*ASME*) *Boiler and Pressure Vessel Code* (hereafter referred to as ASME Code) relies heavily on various nondestructive testing (NDT) methods to assure the integrity of a variety of vessels and components designed under one of several sections to meet specific conditions of service. Section V on Nondestructive Examination (NDE) addresses itself solely to this subject and, like all sections, has a standing committee and numerous subgroups to keep it up-to-date with rapidly changing technology.

This paper will be confined to a general description of those NDE methods referenced in the ASME Code, origin of specific standards documents in other societies, adaptation and modifications to meet ASME Code requirements, and selection of acceptance criteria by other sections. Basically, it will be a guided tour through Section V with a few comments

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and illustrations of specific examples to show how Section V fits into the overall ASME Code, how current it is, and what changes are in the making. Since the entire ASME Code is in a perpetual state of flux, with two addenda published annually, the latest triennial full revision, the 1974 Edition, will be used as the reference point.

General Format of Section V

Section V contains requirements and methods for NDE, detailed in 16 articles, which become ASME Code requirements when referenced by the other sections. These methods are intended to detect surface and internal discontinuities in materials, welds, and fabricated parts and components. Article 1 serves as an introduction and covers general requirements such as manufacturer's examination responsibility, duties of the authorized inspector, written procedures, inspection and examination, and qualification of personnel. The balance of Section V is organized into two subsections, A and B, Appendix A (Glossary of Terms), Appendix B (SI Units) and an Index. Subsection A (Articles 2 to 10) defines the specific NDE methods required by the ASME Code. Subsection B (Articles 21 to 27) contains the basic standards, procedures, and recommended practice documents for each of the NDE techniques as adopted from the American Society for Testing and Materials (ASTM).

Subsection A on Nondestructive Methods of Examination takes up each of the NDT methods separately and spells out the technique parameters that must be applied. These are generally limitations imposed on the referenced basic recommended practice documents listed in Subsection B. In some cases, extensive modifications, additions, or restrictions necessitated by special ASME Code designs will be found here. Subsection A comprises 8 articles (2 through 10) on radiographic, ultrasonic, liquid penetrant, magnetic particle, eddy current, and visual examination plus leak testing.

Subsection B on Documents Adopted by Section V consists of 7 articles (21 through 27), which list by types of NDE the standard methods and recommended practices as adopted from ASTM. These documents, all developed as concensus standards in ASTM committees, primarily Committee E-7 on Nondestructive Testing, plus a few from Committee A-1 on Steel, Stainless Steel, and Related Alloys and Committee B-7 on Light Metals and Alloys, are reproduced here. They differ only from the ASTM versions in the designation, for example, ASTM E 94 becomes SE-94, and ASTM A 609 becomes SA-609, etc. and the addition of a subheading, which calls attention to exceptions, modifications, and limitations on their application. The ASME Code requirements always supercede the SE, SA, or SB document requirements.

Section V also includes Appendix A, a glossary of terms used in NDE, and Appendix B, a list of SI units and conversion factors for those units commonly used in the ASME Code.

Nondestructive Methods in Section V

Each of the NDE methods will be discussed separately to illustrate the manner in which the documents in Subsection B must be modified by the requirements in the appropriate article of Subsection A and, subsequently, their relationship with the referencing ASME Code section. All three sources of requirements must be integrated to satisfy the ASME Code acceptance of a given component, vessel, or structure when NDE is required.

Radiographic Examination

The radiographic NDE method for the detection of internal discontinuities is covered by Articles 2, 3, and 22 in Section V. A list of the radiographic standards of Article 22 are shown in Table 1. Three of these

TABLE 1—*Radiographic standards in Article 22.*

SE-71	Reference Radiographs for Steel Castings up to 2 in. (51 mm) in Thickness
SE-94	Recommended Practice for Radiographic Testing
SE-142	Standard Method for Controlling Quality of Radiographic Testing
SE-186	Standard Reference Radiographs for Heavy-Walled (2 to 4½ in.) Steel Castings
SE-242	Standard Reference Radiographs for Appearances of Radiographic Images as Certain Parameters Are Changed
SE-280	Standard Reference Radiographs for Heavy-Walled (4½ to 12 in.) Steel Castings
SE-446	Reference Radiographs for Steel Castings up to 2 inches in Thickness

standards, SE-94, SE-142, and SE-242, delineate the radiographic technique and alternate methods for controlling its quality, respectively. Articles 2 and 3 select those parameters, to two different levels of quality as prescribed by the referencing design section of the ASME Code, for example, Section III, Nuclear Components, or Section VIII, Pressure Vessels. Additional requirements not covered in SE-94 and SE-142 also are spelled out. Article 2 applies to the highest quality of radiography, whereas Article 3 permits greater latitude in film selection, lower film sensitivity, and less complete documentation. A prominent part of each article is a table prescribing the penetrameter thickness and the acceptable hole diameter for material thickness ranges from below ¼ through 20 in., together with the identification of each penetrameter. The table in Article 2 requires greater sensitivity than 3. Over the past year, ASME committees have been at work to combine these two articles into a single article. The new article appears in the Winter 1975 Addenda to Section V.

The other four standards in Article 22 are the reference radiograph documents for steel castings for different ranges of material thickness. Each standard also is produced from several types of radiation sources. The internal discontinuity types (shrinkage, gas porosity, and nonmetallic inclusions) are depicted by five graded illustrations of increasing severity level. The referencing ASME Code section establishes the acceptance criteria on the basis of severity levels. For example, steel castings in Section III for Class 1 service must meet severity level 2 for all types of graded discontinuities.

It must be pointed up that ASTM Reference Radiographs for Steel Castings up to 2 in. in Thickness (E 71) has been obsolete for several years, no longer appears in the *Annual Book of ASTM Standards,* and is no longer available. It was replaced in 1972 by ASTM Reference Radiographs for Steel Castings up to 2 in. (51 mm) in Thickness (E 446), a much improved document developed along the format of SE-186 and SE-280. When ASTM Method E 446 was incorporated into Section V as SE-446, SE-71 should have been deleted within a reasonable time thereafter. Having both documents in the ASME Code results in unnecessary confusion by causing SE-71 to continue to be referenced in new contracts. It is time to strike it officially from all sections of the ASME Code.

On the other hand, there exists a reference radiograph standard in ASTM that has not been recognized as yet by the ASME Code: ASTM Reference Radiographs for Steel Fusion Welds (E 390). It was developed originally by the Department of Defense primarily for use by the Navy in ship construction. It later was turned over to ASTM for expansion and revision, which resulted in a three-volume document illustrating graded and ungraded weld discontinuities paralleling the format of the casting standards. ASTM Method E 390 is rapidly gaining acceptance by industry in general and deserves consideration for inclusion in the ASME Code.

Ultrasonic Examination

Ultrasonic testing, also intended for the detection of internal discontinuities, is covered by Articles 5 and 23. The 11 ultrasonic standards originating in ASTM and adopted by the ASME Code are listed in Table 2; 5 are under the jurisdiction of ASTM Committee E-7, 5 under ASTM Committee A-1, and 1 under ASTM Committee B-7. Article 5 expands on the basic ASTM standards by the addition of methods and addenda to fill existing gaps in the ASTM documents. One example is ASTM Specification for Longitudinal-Beam Ultrasonic Inspection for Carbon and Low-Alloy Steel Casting (A 609), which covers only straight beam examination of steel castings. The "addendum" to SA-609 in T-524.2

TABLE 2—*Ultrasonic standards in Article 23.*

SA-388	Recommended Practice for Ultrasonic Testing and Inspection of Heavy Steel Forgings
SA-435	Method and Specification for Longitudinal Wave Ultrasonic Inspection of Steel Plates for Pressure Vessels
SA-577	Standard Specification for Ultrasonic, Angle Beam Inspection of Steel Plates
SA-578	Standard Specification for Straight-Beam Ultrasonic Examination of Plain and Clad Steel Plates for Special Applications
SA-609	Standard and Specification for Longitudinal Beam Ultrasonic Inspection of Carbon and Low-Alloy Steel Castings
SB-548	Standard Method for Ultrasonic Inspection of Aluminum Alloy Plate for Pressure Vessels
SE-113	Recommended Practice for Ultrasonic Testing by the Resonance Method
SE-114	Recommended Practice for Ultrasonic Testing by the Reflection Method Using Pulsed Longitudinal Waves Induced by Direct Contact
SE-213	Standard Method for Ultrasonic Inspection of Metal Pipe and Tubing for Longitudinal Discontinuities
SE-214	Recommended Practice for Immersed Ultrasonic Testing by the Reflection Method Using Pulsed Longitudinal Waves
SE-273	Standard Method for Ultrasonic Inspection of Longitudinal and Spiral Welds of Welded Pipe and Tubing

covers angle beam examination of steel castings. Similarly, T-525 covers ultrasonic examination of bolts and studs, which has no counterpart in ASTM. Other examples are the ultrasonic examination of welds by both the straight beam and angle beam methods, the examination of weld deposited cladding, and examination for thickness determination by either the pulse-echo or resonance methods.

Liquid Penetrant Examination

The liquid penetrant method for the detection of discontinuities open to the surface of ferrous and nonferrous materials is detailed in SE-165, Article 24 (Table 3). Further refinements and modifications to SE-165 are given in Article 6. A recent revision of E-165 more closely conforms

TABLE 3—*Liquid penetrant standards in Article 24.*

SE-165	Standard Methods for Liquid Penetrant Inspection
SE-270	Standard Definitions of Terms Relating to Liquid Penetrant Inspection

to the provisions of Article 6 and eventually will result in a revision of that article. In the absence of a visual standard of graded indications, the referencing ASME Code sections verbally describe the acceptance criteria of the several types of indications.

Magnetic Particle Examination

The magnetic particle method is intended for detection of cracks and other linear discontinuities in ferromagnetic materials. Sensitivity is greatest for surface discontinuities and falls off rapidly with depth below the surface. Article 25 (Table 4 lists standards SE-109 for the dry powder method and SE-138 for the wet method. Other provisions and parameters are defined in Article 7.

TABLE 4—*Magnetic particle standards in Article 25.*

SE-109	Standard Method for Dry Powder Magnetic Particle Inspection
SE-138	Standard Method for Wet Magnetic Particle Inspection
SE-269	Standard Definitions of Terms Relating to Magnetic Particle Inspection

Acceptance criteria are defined in the referencing design sections of the ASME Code. For several years, conflicting acceptance standards have existed for steel castings in Sections III and VIII. Section III, NB 2545.3, considers linear indications less than 1/16 in. long as irrelevant and sets limits of indication length for three ranges of material thickness. By comparison, Section VIII, Division 1, Appendix VII, UA 82 (3) permits no linear indications (hot tears and cracks). This is virtually impossible to achieve and, hence, an unrealistic requirement. A finite measurement minimum length must be established, such as the Nuclear Section has done.

It should be noted that Section VIII references ASTM Reference Photographs for Magnetic Particle Indications on Ferrous Castings (E 125) and sets reasonable acceptance criteria for nonlinear discontinuities such as shrinkage, inclusions, chills and chaplets, and porosity. Since ASTM Method E 125 is referenced in a design section, it seems appropriate that it should also be listed in Article 25, Section V, but for some reason it is not.

Eddy Current Examination

The eddy current method of flaw detection is covered by Article 8 and the four ASTM standards listed in Article 26 (Table 5). This is a relatively new method with many more documents in various stages of development in ASTM Committee E-7.

Visual Examination

Article 9 prescribes the required criteria for visual examination to determine such things as the surface condition of a part, alignment of mating surfaces, shape, or evidence of leaking. Access, lighting, and angles of

TABLE 5—*Eddy current standards in Article 26.*

SE-215	Recommended Practice for Standardizing Equipment for Electromagnetic Testing of Seamless Aluminum-Alloy Tube
SE-243	Tentative Recommended Practice for Electromagnetic (Eddy Current) Testing of Seamless Copper and Copper-Alloy Heat Exchanger and Condenser Tubes
SE-268	Standard Definitions of Terms Relating to Electromagnetic Testing
SE-309	Tentative Recommended Practice for Eddy Current Testing of Steel Tubular Products with Magnetic Saturation

vision are important factors in performing either direct or remote visual examination, depending on existing conditions. When this article is invoked by a referencing design section, the visual examination must be done to a written procedure and the results of the examination incorporated into a written report.

Leak Testing

Article 10 covers the requirements and methods for the performance of leak testing using Gas and Bubble Testing, the Halogen Diode Detector, the Helium Mass Spectrometer Reverse Probe (Sniffer), and the Helium Mass Spectrometer Hood methods. It is not a detailed procedure, but is intended to provide the basis for the development of such procedures by the manufacturer. Only recently has ASTM addressed itself to the development of leak testing standards and only two have been adopted by the ASME Code, Article 27 (Table 6).

TABLE 6—*Leak testing standards in Article 27.*

SE-425	Standard Definitions of Terms Relating to Leak Testing
SE-432	Standard Recommended Guide for the Selection of a Leak Testing Method

Personnel Qualification

Any NDE is dependent upon the ability of a person to conduct the test properly and to be able to interpret the results. In an effort to assure that adequately trained and experienced NDT personnel are used, the ASME Code requires that they be qualified to meet the requirements of SNT-TC-1A Recommended Practice for Qualification and Certification of NDT personnel. This document was developed by the American Society for Nondestructive Testing (ASNT) and was revised in 1975 to cover seven methods of NDT. There has been and is considerable controversy concerning the adequacy of SNT-TC-1A. Suffice it to say, that the ASME Code enables manufacturers to verify the competence of NDT personnel through a system of audits.

Conclusion

The ASME Code makes extensive use of NDT methods in order to assure freedom from failure of vessels, components, and structures designed to its rules. Although the ASME Code traditionally has been slow to change, it is moving more rapidly to adopt advances in NDT technology which usually are initiated in ASTM documents. Even so, there is generally a lag of at least a year as the proposed ASTM revisions or new documents move through the many ASME Code committees. Unfortunately, too, there still exist inconsistencies between ASME Code sections involving interpretation of NDT results for comparable applications. Gradually, these are being eliminated.

C. H. Hastings[1]

Military Standards for Nondestructive Tests

REFERENCE: Hastings, C. H., "**Military Standards for Nondestructive Tests,**" *Nondestructive Testing Standards—A Review, ASTM STP 624*, Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 30–37.

ABSTRACT: The growth of nondestructive testing (NDT) technology, its control documentation, application philosophy, and management of its specifications tree are traced from 1920 to the present. The status of military documents on NDT relative to the technology is discussed, inadequacies are defined, and problems resulting from the gap are listed. Although the technology has grown far beyond the scope of coverage in military specifications and standards, this situation can be remedied by the several approaches which are suggested. Three recommendations are made as a suggested optimum, implementable, solution.

KEY WORDS: nondestructive tests, standards, quality control, specifications, management, military procurement, test applications

Introduction and History

This paper is concerned with the documents by which nondestructive tests (NDT) are defined and controlled for use in acceptance inspection by the Department of Defense (DOD). Of the 39 documents included in a 1973 survey,[2] 22 are standards and 17 are specifications. According to the *Defense Standardization Manual*[3] "a Specification is a document intended primarily for use in procurement and which describes the essential technical requirements for...the (NDT) procedures by which it will be determined that requirements for the procured item will be met. A Standard is

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[2] Meister, R. P., Flora, J. H., Mitchell, D. K., Rhoten, M. L., and Queen, R. L., "Program Analysis, Standardization Area Assignment for Nondestructive Testing and Inspection," Final Report to the Department of the Army, Army Materials and Mechanics Research Center, from Battelle Columbus Laboratories, Columbus, Ohio, 10 Sept. 1973.

[3] "Standardization Policies, Procedures, and Instructions," *Defense Standardization Manual*, 4120.3M, Jan. 1972.

primarily to serve the needs of designers and to control variety. It establishes engineering and technical limitations and applications for (NDT)." Of course, standards also include physical hardware used for calibration of test apparatus, pictorial standards used to define acceptance limits, or base line numerical standards for a variety of NDT applications. With no intent to reopen the semantics discussion, this paper will discuss documents, specifications and standards.

The U.S. Army and Navy were pioneers of NDT development in the 1920 to 1930 decade. Then, as now, the fallibility of human industrial operations led to the desire for better inspection to minimize critical failures in our national defense machinery. Development of industrial radiography in the United States began at Watertown Arsenal (Dr. H. H. Lester) in 1922 and led to the first military specification for that method around 1935. It was called Radiographic Inspection, Army Experimental Specification (AXS)-476. Also, in the 1920s, Major William Hoke of the Army, working in the National Bureau of Standards on gage blocks of improved dimensional stability, discovered the magnetic particle test method. This method, developed by Prof. A. V. deForest of Massachusetts Institute of Technology, was explored actively and used by the Army and Navy during the 1930s. Military specifications for magnetic particle tests first appeared in the early 1940s, prepared by the Army Air Corps/Navy Bureau of Aeronautics (wet technique) and the Navy Bureau of Ordnance and Army Ordnance (dry powder technique). Dr. R. F. Mehl, Naval Research Laboratory, pioneered gamma ray radiography using radium in the later 1920s, leading to its use in shipyards during the 1930s. By the late 1930s to early 1940s, military specifications for radiography and magnetic particle were in evidence and proliferating in all branches of the military for specific applications. The recognition of the need for different requirements generated separate specifications and standard radiographs for ship welds, cast armor, welded gun mounts, aircraft castings, and other products. Similar expansion of the number of specifications was evident in the magnetic particle testing area for differing needs.

In 1944, a meeting was held at Watertown Arsenal to attempt consolidation of the growing list of NDT specifications within the Army and Navy. The joint Army-Navy specifications era had arrived (JAN specifications). At these meetings, it became apparent that the technologists could consolidate and agree on the technology, but they remained divided on the procurement management aspects of NDT. The Army Air Corps and Navy Bureau of Aeronautics emerged on one side of the debate and the rest of the Army and Navy on the other. Obviously, aircraft were designed primarily by the aircraft industry because of the continuity of its interest in peacetime and war. However, guns, tanks, ships, etc., were designed and specified by the military so that their technology could advance even during peaceful times. Aircraft are aircraft, in principle, peace or war, but battleships are battleships, exclusively for war.

If this situation is evaluated, it leads to the conclusion that the aircraft industry did an excellent job with casual monitoring from the military by circuit-riding NDT inspectors. The rest of the military hardware in World War II literally was inspected and accepted by trained government inspectors working out of Army District Offices and Naval Districts.

Because of this difference in management approach to inspection (justified), the consolidation of NDT specifications under the JAN program was abortive. Army-Navy aeronautical went one way, the rest of the military went another, and NDT specifications continued to proliferate, for reasons managerial, not technical.

Following World War II, fluorescent penetrant tests were introduced, and in 1948 pulsed-echo ultrasonic techniques were being exploited. Although specifications for penetrant tests soon were prepared by the Army/Navy Aeronautical group, ultrasonic specifications were slow in being realized due to the technical complexities of the method which made preparation of a general specification cumbersome.

Armed with a multitude of experiences in applying NDT to military production during World War II, and with great appreciation for the future potential of NDT for industrial inspection and quality control, most knowledgeable workers in the field attempted to develop new methods. During the period from 1946 to 1965, military specifications on NDT nearly were ignored, the majority of effort being spent on expanding the technology by exploring all physical principles for their applicability. Only brief attention was paid to specifications when, in the early 1950s, another effort at coordination under the MIL Specifications System was initiated following the creation of the DOD in 1947. Again, little was achieved other than a renumbering of JAN specifications to MIL specifications and for the same reasons. Generalization of NDT methods does not work well, and the different administrative approaches employed by the Army, Navy, and Air Force (Air Force at that time had become an independent department of the military) led to continued fragmentation of NDT documents.

As of 1973, there were 39 MIL specifications and standards dealing with NDT; 21 of these cover radiography or related aspects, 5 treat magnetic particle tests, 5 treat ultrasonic tests, 1 each penetrant and eddy current testing, and 6 deal with other aspects such as personnel qualification, Navy piping NDT, castings inspection, and general NDT program requirements for aircraft and missile materials and parts.

If this list of MIL specifications and standards is compared with NDT technology, as it is known today, it must be concluded that the specifications and standards have not kept pace. The expansion of the technology which began in the post World War II period has been highly successful, even though the military documents have been neglected.

Technical Application of NDT Specifications

In the late 1930s and early 1940s, the Naval Bureau of Ordnance had issued drawings for construction of 5-in. gun mounts on which radiography and magnetic particle tests were required for specific critical welded joints. Pictorial radiographic standards for allowable defects were provided separately and procedures for testing were referenced in test technique manuals or procedures. Magnetic particle tests were used to detect stringers or laminations in the cut edges of steel plate prior to welding. In other words, the Navy used NDT in concert with design engineering and welding process control to aid in production of a better gun mount. Repairs of defects were requested, followed by reinspection of the repaired welds.

These procedures were effective before formal specifications for magnetic particle tests had been written. Only procedural technical guidance manuals were available. This approach was made workable by communication between people, designers working with welding engineers, and NDT engineers. NDT engineers worked with inspectors employing direct personal contact, Navy to contract fabricator. The operation functioned successfully.

In another example of early NDT application philosophy, Watertown Arsenal, working with Detroit Tank-Automotive Center for the Army, used radiography for process control and inspection of production cast armor for army tanks. Based upon the relative difficulty of casting the various shapes and sizes of armor and the service vulnerability of these castings (exposure to attack), radiographic position drawings were prepared for all castings. These drawings called for an appropriate radiographic procedure specification. The casting was laid out in X-ray view areas for standard film sizes. Each area was numbered and referenced to a chart on the drawing which specified the sampling plan and acceptance limits for the area. Radiography was used on a 100 percent basis during a "pilot plant" or pouring technique development phase of manufacture. After radiographic quality had been adequately demonstrated in the pilot-plant phase, full "production" phase was permitted to begin on a reduced radiography basis. In production, only 1 out of 10 castings were X-rayed, depending on a lot size, and only critical areas were radiographed routinely on each casting inspected. A few additional views were taken at random, and the random views moved around so that complete coverage was obtained after a given number of castings had been examined. If these random views revealed rejectable defects, the casting was forced back into the pilotplant 100 percent coverage situation until the foundry problems had been remedied. The goal was to employ NDT as a control on the foundry process and to reduce, by sampling, the inspection of full production. This entire radiographic plan was coordinated between the casting designer, the NDT engineer, the foundry industry, and the Army Ordnance inspectors who were trained at Watertown Arsenal and were resident at the foundry facility. The government inspector interpreted all radiographs produced by the contractor (foundry) X-ray laboratory. Acceptance decisions were also made by the Army inspector.

These NDT inspection plans were in being in the 1940 to 1945 time frame. The coordinated key roles of designers, NDT engineers, industrial production metallurgists, and government field inspectors (NDT specialists) were emphasized as essential to the application of nondestructive tests. Without the coordination between the entire team, the gap between NDT specifications and their application to real production problems could not have been bridged.

Management of NDT Specifications Tree

In order to be most widely applicable, MIL specifications and standards on NDT tend to be general rather than specific to a given product. As previously noted, generalization of NDT technology is unsuccessful because of the sensitivity of the methods to product variables such as kind of material, processing, shape, size, surface roughness, rate of inspection throughout, acceptance limits, causes of failure, and many others. The majority of MIL documents on NDT do not contain acceptance criteria nor specific test procedures for any given product. For this reason, the few nondestructive tests that are covered at all by MIL documents are covered so generally as to be useless or completely insufficient. They cannot stand on their own feet without supplemental detailed specifications and test procedures for specific hardware items. The authors of these documents know this, but laymen may not appreciate this fact.

During World War II, when the number of NDT techniques and applications were relatively few and much of the hardware was designed by the military, the NDT specification writer could get close to the design agency and write the necessary supporting procedures. Now that the designs, production, and responsibility for quality are vested in the industrial contractor, the general MIL specifications and standards on NDT seldom are interfaced adequately with the required detailed specifications and procedures. It appears that the NDT quality engineering job is manned insufficiently at the fragmented DOD procurement planning level (Army, Navy, and Air Force) to permit adequate follow through from the basic MIL specifications to the necessary detailed documents. The military NDT specifications writer of 1945 expected and usually got that follow through from the procuring activities. Because of changes in the approach to procurement packaging and contracting since 1965 (the Defense Contract Administration Services came into existence that year) the follow through has been largely absent.

Following the specifications tree to the top, prime guidance for procurement package preparation is provided by the Armed Services Procurement Regulations (ASPR). A reading of Section XIV of the ASPR, covering "Procurement Quality Assurance," finds no mention of the NDT technology. Reference is made to Quality Program Requirements (MIL-Q-9858) and Inspection System Requirements (MIL-I-45208), the top tier documents. Neither of these documents mentions the existence of NDT technology.

Nondestructive testing is disconnected from the procurement cycle, both at the top and bottom of the specifications tree. This technology is in the ball game only haphazardly, if at all, rather than by deliberate plan. With some exceptions, primarily in the aircraft industry and the Air Force, NDT is not recognized by the military procurement specifications tree. It frequently floats in space, separated from reality at the top and the bottom.

Two changes in DOD procurement policy have generated this large leak in the quality control dike.

1. The disestablishment of Army Ordnance District Offices and Naval District Offices with their Chiefs of Inspection and trained NDT specialists. This action occurred in 1965 when Defense Contract Administration Service (DCAS) was given its procurement assignment.

2. The transfer of the total responsibility for hardware design and quality to the industrial contractor from the Army Arsenals and Navy establishments.

There were good, justifiable reasons for instituting these policy changes, but they did result in NDT being left high and dry in the Army and Navy. Since the Air Force always has operated more or less according to the second change just mentioned, the impact of these policy changes was negligible in their case. Even in the Air Force, the communications link between NDT technology and its application to procurement has been weak at times. During the past five years, the Air Force has taken significant action to improve this situation. It is too early to judge the effectiveness of these efforts.

Discussion of Problems and Alternatives

Several problem areas have been highlighted in the foregoing paragraphs and are listed as follows.

1. Existing MIL specifications and standards fall far short of representing the complete NDT technology as it is understood today.

2. Existing MIL documents on NDT are usually general, rather than specific as to hardware applicability, and, therefore, incomplete. As such, they are frequently unusable unless supplemented by detailed documents which are specific to particular hardware.

3. Frequently, there is no qualified NDT engineer in a position to review the proper application of NDT MIL specifications and standards in Army, Navy, and Air Force procurement packages. In such cases, the procurement packages may not be buying the benefits of NDT technology for inspection and product assurance.

4. MIL specifications and standards on NDT are not referenced in the top tier military procurement documents dealing with quality assurance, that is, Armed Services Procurement Regulations MIL-Q-9858 (Section XIV), and MIL-I-45208. Because of this lack of reference, the application of NDT to procurement package preparation is haphazard, nonexistent, or dependent on the recognition of need by individuals sometimes unqualified.

Alternatives for solutions to these problems are considered next. Taking Problems 1 and 2 together because of their interrelationship, the complete spectrum of NDT can be made available for military procurement by expanding the number of general method/technique specifications and standards. Although arbitrary, one breakdown of the scope of NDT[4] shows 6 methods, subdivided into 20 method variations and 46 techniques. Thus, 46 general MIL specifications of standards would be needed, even if no duplication existed among the 3 military services (for example, only 1 specification on radiography instead of the 21 which now exist). In an oversimplification of the facts, consider 1 000 critical military products in each of 20 product categories (castings, forgings, composites, weldments, etc.), each requiring 2 nondestructive techniques for quality evaluation, we arrive at 40 000 detailed specifications, supplemented by an equal number of operating procedures for a total of 80 000 documents required to control the inspection effort. Now, if only one duplication of documents is required for each of the three services because of varying application demands between Army, Navy, and Air Force, this number is inflated to 240 000 documents (0.25 million specifications).

As a minimum, 276 general MIL specifications would be required (46 methods times 3 services, times 2 or more applications areas such as missiles versus land vehicles versus ships versus naval aircraft). The supporting documents must be prepared by the design agency, usually industry, so as to be adequately specific to each hardware inspection problem. The contribution made to the specifications system, resulting from the 276 general MIL specifications, is open to question. Recall that the general documents tend to become less definitive, therefore more

[4] "Nondestructive Evaluation," National Materials Advisory Board Report, NMAB-252, June 1969.

useless, in proportion to their generality. The control on the NDT inspection really is achieved by the detailed test procedures.

An attractive possibility is to eliminate the need for the 276 general MIL specifications or standards by substituting a single NDT program planning requirements standard, paralleling MIL-Q-9858. This document should contain the requirements peculiar to selection and application of NDT and should contain much better guidance than given by the vague generalities of MIL-Q-9858 or MIL-I-45208.

Regarding Problem 3, additional NDT engineering personnel are required in the government services. If the military specifications are to be expanded to cover the field, a multiyear contract and in-house effort, involving considerable engineering manpower, will be required. More important, NDT engineering manpower is required at the government agencies which develop procurement packages to select those test methods and MIL standards necessary to control quality evaluation.

If the procurement proceeds without adequate NDT consideration, experience teaches that an even larger cadre of NDT manpower is required to wastefully cope with crisis problems arising from design and manufacture of failure-prone or inadequately performing hardware. The old cliché, do it right the first time, appears to be appropriate.

To tie NDT technology into the specifications tree at the top, NDT could be a required subject for all quality control/product assurance intern training for personnel at military procurement package-preparing organizations. In addition, a top tier NDT program planning document is needed as a basic reference in Armed Services Procurement Regulations or MIL-Q-9858/MIL-I-45208 or both. Guidelines for applicability of NDT could be included in Section XIV of ASPR.

Recommendations

Considering the problems and alternative techniques for handling them, the following recommendations, believed to be implementable are made.

1. Consistent with present DOD policy to place responsibility for design and manufactured quality on the industrial contractor, replace existing MIL specifications and standards with a single MIL standard on NDT Inspection Program Requirements, patterned after Inspection Program Requirements, Nondestructive, for Aircraft and Missile Materials and Parts (MIL-I-6870D). This document was prepared by the Air Force and made effective 8 May 1975. NDT Personnel Qualification and Certification (MIL-STD-410) should be retained to support MIL-I-6870D.

2. Staff military procurement package-preparing organizations with qualified NDT engineers to provide technical input (judgment) to the package preparation and to review and approve contractor response to the MIL-I-6870D-type document.

3. Tie the MIL-I-6870D-type document into ASPR, Section XIV, so that NDT becomes a recognized part of the military specifications tree.

G. J. Dau[1]

Codes and Standards for In-Service Inspection of Nuclear Power Plants

REFERENCE: Dau, G. J., "**Codes and Standards for In-Service Inspection of Nuclear Power Plants,**" *Nondestructive Testing Standards—A Review, ASTM STP 624*, Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 38–52.

ABSTRACT: The mandatory periodic in-service inspection of commercial nuclear power plants in the United States is governed by the American Society of Mechanical Engineers (*ASME*) *Boiler and Pressure Vessel Code,* Section XI, "Rules for In-service Inspection of Nuclear Power Plant Components." The scope of these rules is indicated, as well as a summary of the requirements that have evolved as the ASME Code was developed. Recent experience with austenitic pipe inspection is used to illustrate the interaction of ASME Code requirements, inspection technology development, and fabrication practice. Because the performance of these examinations requires skilled people, comments are made about certification and manpower availability.

KEY WORDS: inspection, nondestructive tests, standards, performance tests, nuclear power plants

The design, construction, and operation of commercial nuclear power plants is governed by the American Society of Mechanical Engineers (*ASME*) *Boiler and Pressure Vessel Code* (hereafter referred to as the ASME Code). Two specific sections of the ASME Code deal exclusively with nuclear systems. Section III, "Nuclear Vessels," defines the design, fabrication, and construction procedures for components for nuclear pressure boundaries [*1*].[2] Section XI, "Rules for Inservice Inspection of Nuclear Power Plant Components," states the mandatory requirements for periodic in-service inspection that must be met by applicants for licenses to build and operate nuclear power stations in the United States [*2*].

The purpose of this article is to summarize the more important features

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[2] The italic numbers in brackets refer to the list of references appended to this paper.

of the ASME Code, Section XI. Those interested in a more thorough discussion are referred to the ASME Code itself as well as several recent articles [*3–8*]. The comments that follow address the topic from the viewpoint of a historical perspective of the ASME Code evolution, a summary of its provisions now in effect, a discussion of austenitic pipe inspection as a current problem, and conclude with a discussion of manpower requirements.

Historical Perspective

With the development of the commercial nuclear power industry, it was recognized that components in a nuclear pressure boundary must be viewed in a somewhat different light than those used in conventional fossil-fueled plants. Initially, the primary concern was that radioactivity could preclude routine inspection, and any repair or maintenance would be difficult to accomplish. As a consequence of this concern, the initial effort was to increase the design, fabrication, and construction standards for nuclear components above those applied to the familiar fossil-fueled power plants. In 1963, the first response to this desire for higher-quality standards appeared in the ASME Code, Section III, "Nuclear Vessels." At that time, it was believed that the higher standards would eliminate the need for periodic inspection of the system during its operational lifetime.

As plant operation experience was developing, the record of operationally induced component defects requiring repairs generated concern about the original premise for not requiring periodic in-service inspection. In 1966, the U.S. Atomic Energy Commission (USAEC) began to develop criteria for the in-service inspection of nuclear reactor coolant systems. Eventually, in late 1967 an USAEC-industry cooperative code development program was initiated under the auspices of the American National Standards Institute (ANSI) with the sponsorship of ASME. An initial "Draft Code for In-service Inspection of Nuclear Reactor Coolant Systems" was published in 1968. This was followed by its formal publication in 1970 in the ASME Code, Section XI, "In-service Inspection of Nuclear Reactor Coolant Systems." In 1971, the USAEC formally accepted Section XI of the ASME Code by incorporating it into its "Codes and Standards for Nuclear Power Plants" [*9*]. It also fulfills the requirements of AEC General Design 32 [*10*] with respect to periodic inspection and testing of important areas and features of components which are part of the reactor coolant pressure boundary. Thus, Section XI became a mandatory requirement for anyone seeking a license to build and operate a nuclear power station in the United States.

As experience was gained with use of the ASME Code, limitations or ambiquities were noted in its procedures. When this occurred the Section XI Committee acted to resolve these issues. The results of these changes were incorporated into the ASME Code by issuance of Addenda. In 1974, all prior changes were incorporated and a revised edition of Section XI was issued (1974 Edition). Since then four additional addenda have been published. The two with the most importance for in-service inspection (ISI) are the Summer 1974 and the Winter 1975 Addenda. The former provides additional or updated requirements for evaluation of defects during an in-service inspection. The Appendix III which prescribes the procedure for inspection of ferritic pipe inspection is the subject of the Winter 1975 Addenda.

Excellent discussions of the considerations entering into Section XI revision and augmentation are given in Refs *4*, *5*, and *7*.

ASME Section XI Requirements

The jurisdiction of ASME Code, Section XI, rules (In-service Inspection) begins when the component has met the requirements of ASME Code, Section III (Fabrication). The scope of this inspection standard is the in-service inspection of nuclear vessels, piping, pumps, valves, and their supports; it also includes in-service testing of pumps and valves. Because Section XI deals with the operational phase of a pressure system, it represents a significant departure from the prior ASME policy that restricted itself to design, fabrication, and construction. In addition, it extends equal recognition to the importance of performance testing of certain components, such as valves and pumps, and to the basic structural integrity. The remainder of this section is devoted to providing a summary of the more important aspects for both the curious and those who desire a more thorough understanding. For the latter case, this can serve as a starting point followed by a thorough study of the ASME Code itself and selected references.

Format

An understanding of the organization of Section XI is helpful to gain an understanding and appreciation of its contents and scope. The format of Section XI establishes three divisions:

1. Rules for Inspection and Testing of Components of Light-Water Cooled Plants
2. Rules for Inspection and Testing of Components of Gas-Cooled Plants
3. Rules for Inspecting and Testing of Components of Liquid-Metal Cooled Plants

For Division 1 (the same format will be used for Divisions 2 and 3) three subdivisions exist: (*a*) Inspection of System Components, (*b*) Testing of pumps and Valves, and (*c*) Inspection and Testing of Containment Structures.

The subdivisions are divided further into the following sections: General Requirements, Class 1 Components, Class 2 Components, Class 3 Components, Component Supports, Core Internal Structures, Pumps and Valves.

At the present time, task groups are working on development of rules for inspection of liquid metal cooled reactors and gas cooled plants. Task groups are expected to be formed to develop inspection requirements for containment structures, core internals, component supports, as well as the requirements applicable to modifications, alterations, replacements, additions, and spare parts. The ultimate goal is to have rules in place to govern the inspection of almost all areas of a nuclear power station once it becomes operational.

The specific rules now in place (Class 1, 2, and 3 Components, Pumps, and Valves for Light-Water Cooled Reactors) reflect the initial priority to develop requirements for the components with the greatest safety significance. A discussion of the requirements for these subsections follow.

Class 1 Components

The Class 1 components include those that encompass the reactor coolant system and portions of systems connected thereto, located within the confines of the primary reactor containment structure. For example, this includes the outermost isolation valves in the system piping that penetrates the containment. The general philosophy for this class is to examine all welds before plant operation commences. The purpose of this step is twofold: to detect any flaws that are developed during construction and to furnish a benchmark for comparison with future inspections. Where redundant loops exist, examination of only one loop is required.

After commercial operation begins, the intent is to have all components inspected once during the first inspection interval. Initially, the inspection interval was specified as ten years with a certain percentage of the total examination covered in three inspection periods within this interval [*3*]. This program of equal-spaced examinations now is referred to as Program B. An unequal inspection interval (called Program A) was developed recently as an alternative method [*7*]. Although the number of inspections in each program is equal, Program A takes advantage of the gains resulting from complete in-service examination performed early in the service lifetime. Under this program, 50 percent of the total number of inspections during the plant lifetime would be completed by the end of the 10th year of plant service. Under Program B, this amount of inspection would not be completed until the end of the 20th year. Recent increased attention on assessing the influence of inspection on failure probabilities of nuclear vessels prompted this change. Table 1 compares the alternate inspection

TABLE 1—*Alternate inspection intervals.*

Inspection Interval	Program A	Program B
1	3 years after start-up, $R = 20^a$	10 years after start-up, $R = 9$
2	7 years following 1st interval, $R = 400$	10 years following 1st interval, $R = 42$
3	13 years following 2nd interval, $R = 8100$	10 years following 2nd interval, $R = 134$
4	17 years following 3rd interval	10 years following, 3rd interval

[a] $R = \dfrac{\text{failure probability without inspection}}{\text{failure probability with inspection}}$ (from Ref 7).

intervals. Also included in this table is a figure of merit, R, that quantifies the enhanced reliability from in-service inspection. This figure is defined as the failure probability of a component without benefit of in-service inspection divided by failure probability of a component with the benefit of in-service inspection. As the table shows, in-service inspection substantially enhances confidence in component performance. Furthermore, concentrating inspection early in service life provides even greater assurance of component performance.

Recent changes increased the amount of vessel material examined during each inspection interval. The requirement for 100 percent examination of welds during both preservice examination and the first interval is intended to establish the equivalency of structural integrity among weld seams. Furthermore, a comparison of results after the first interval gives assurance that no service induced deterioration has occurred during the first inspection interval. The requirements for inspection of a pressure vessel and Class 1 piping and components are summarized in Table 2.

Recently, rules for inspection of steam generator tubing in a pressurized water reactor (PWR) system were incorporated into Section XI [7]. Procedures have been developed for eddy current examinations; however, development of acceptance standards has not been completed. When these are completed, it is anticipated that these procedures and acceptance standards will ultimately appear as Appendix IV of Section XI.

This addition resulted because service experience with steam generator tubing under certain conditions of secondary water treatment have demonstrated an unanticipated degree of tube corrosion. Tubes with an unacceptable level of deterioration are required to be removed from service by tube plugging techniques. The rules for tube plugging are under development for addition to Section XI.

TABLE 2—*Summary of weld examination requirements.*

Vessel Components Examined	Preservice Examination	In-service Examination Inspection Intervals			
		1st	2nd	3rd	4th
Welds in shell and heads[a]					
% welds	100	100	60	60	60
% vessel surface scanned	50	50	30	30	30
% vessel metal volume examined	33	33	20	20	20
4, inlet, 4, outlet nozzles[b]					
% welds	100	100	100	25	25
% nozzle, shell scanned surface	66	66	66	16	16
% nozzle, shell metal volume examined	80	80	80	20	20
Piping welds[c]	100	100	100	100	100
Welds in pump casing[c]	100	100	100	100	100
Welds in value bodies[c]	100	100	100	100	100

[a] The percentage values listed represent the percent of the total surface and total metal volume of the PWR reactor vessel, respectively.

[b] The percentage values represent the percent of the total interior surface of the nozzle bore and shell interior surface within the required examination volume, and the corresponding total metal volume, respectively.

[c] Examinations concentrated upon the components of on recirculating loop where redundant loops exist.

Class 2 Components

The ASME Class 2 components in a nuclear power plant may be broadly categorized into three groups:

1. Systems or portions of systems containing high-energy fluids such as the steam and feed-water streams located outside of primary containment
2. Systems required to perform a safety function such as shutting down the reactor to the cold shutdown condition
3. Systems required to function in order to mitigate the consequences of an accident (for example, emergency core cooling systems)

The inspection philosophy adopted for this class is similar to that used for Class 1 components. The most extensive examination requirements are applied to components having the greatest service loads. However, in contrast to Class 1, an additional requirement is imposed on emergency core cooling systems. This requirement is in the form of control of the fluid chemistry to minimize corrosive effects and reflects the recognition of the potential for corrosion that exists in these systems that must stand in water-flooded condition at readiness to operate when needed. Specifically exempted from examination are low energy systems whose design pressure and temperature are less than 275 psi (1.9 MPa) and 200°F (93°C) respectively. Also exempted are components whose nominal pipe diameter is 4 in. (10 cm) and smaller.

Class 3 Components

The ASME Class 3 components are used primarily in systems that function to transport heat from Class 2 components to the ultimate heat sinks of the nuclear power plant. Typical examples are those supplying cooling water to reactor residual heat removal systems, emergency core cooling systems, and post-accident heat removal and containment cleanup systems. These functions have sufficient redundancy so repair can be performed without interruption of system function. For this reason the inspection program consists of periodic system hydrostatic tests conducted at the end of each inspection interval when components may be examined visually for leakage, structural distress, or corrosion. In addition, at least three visual examinations during system operation are required during each inspection interval.

Functional Testing of Pumps and Valves

Rules for in-service testing Class 1 pumps and valves for light-water plants have been developed, and similar rules are being prepared for Class 2 and Class 3 pumps and valves. These rules represent a major addition to the original philosophy of inspecting the pressure boundary to ensure structural integrity in that emphasis is placed upon operating characteristics to improve assurance that the pumps and valves will perform as required when needed.

Tests for valves include exercising the valves and the determination of leak rates. For centrifugal and displacement type pumps, in-service test parameters include speed, inlet pressure, differential pressure, flow rate, vibration amplitude, and bearing temperature. In addition, such characteristics as lubricant pressure are observed. The criteria cover acceptable ranges, a so-called alert range, and a required action range for each of the parameters.

Ultrasonic Examination Procedures

Although the ASME Code has the flexibility for substitution of equal but alternate inspection methods, only ultrasonic methods are currently finding widespread usage for in-service inspection. This occurs because the Section XI volumetric inspection requirements can be satisfied easiest by ultrasonic techniques. Specific incidents occurred during the early application of Section XI that indicated a problem existed in trying to quantify defects with ultrasonic techniques [*4,5*]. Accordingly, a task group was formed to define rules governing ultrasonic examination procedures more completely and rigidly [*4*]. The results was the incorporation of Appendix I, "Ultrasonic Examination," into Section XI which sets forth the mandatory requirements for use during in-service inspection of the vessel. The requirements include: calibration blocks, instrument calibration, transducer characteristics for both longitudinal and shear wave inspections, and information recording. The procedures used for examination of the system are quite specific with regard to orientation of the beam with respect to welds, nozzles, etc. Overall, these procedures should produce a high degree of reproducibility of ultrasonic examinations. The use of these procedures is mandatory for all vessels welds which means butt welds, 2½ to 12 in. (6.35 to 30.5 cm) thick in medium strength low alloy ferritic steels. A good review of this topic is given by Hedden [*4*].

The scope of mandatory procedure coverage was extended to ferritic piping by issuance of Appendix III, "Ultrasonic Examinaton Method for Class 1 and 2 Components made from Ferritic Steels." This appears as the 1975 Winter Addenda to Section XI.

Examination Evaluation

The volumetric examination procedures specified by Section XI to map defect indications in components are supplemented with rules for uniform characterization of the observed indications. Flaw standardization criteria are stated to enable the transformation of an observed indication into an appropriately oriented geometrically defined planar flaw. The defined flaw then is compared directly with acceptance standards expressed in the same geometric flaw parameters. These "allowable indication standards" provide the basis for determining the acceptability of flaws before components are commissioned for or returned to service.

Those flaws that exceed in size those permitted in the acceptance standards may be evaluated using a nonmandatory procedure described in Appendix A. The procedure is an application of linear elastic-fracture mechanics to a given flaw using such factors as flaw shape, flaw orientation, flaw location, stress intensity factors, and the stress fields at the flaw location for normal, upset, emergency, and faulted loads. The worst flaw orientation is used for any given combination of loads.

The procedures recognize the limitations of ultrasonic examination techniques to define precisely the dimensions, areas, and orientation of flaws. To overcome these factors, many simplifications and conservatisms are incorporated to reduce the need to determine flaw size and orientation precisely.

Repair

Having established techniques to locate and evaluate flaw conditions, it is appropriate then to have a procedure available to guide corrective action for those indications judged serious enough to prevent the component from being returned to service. Consequently, five repair procedures were developed and incorporated into Section XI. These procedures were developed while considering the difficulties of component repair *in situ* under plant conditions that severely restrict flexibility in the choice of methods and procedures.

Recapitulation

In summary, Section XI, "Rules for Inservice Inspection of Nuclear Power Plant Components," stipulates what items are to be inspected, the frequency of inspection, the examination procedure to be used, criteria for evaluation of flaw indications, and standards against which to compare the flaw indication. Finally, if a flaw indication is judged to be severe enough to prevent the component from being returned to service, suitable repair procedures are specified also. The jurisdiction and interaction of different sections of Section XI are illustrated in flow chart form in Fig. 1. The alpha-numeric designation (IWB-3420, IWB-3114, etc.) in each step is a reference to the specific article in Section XI. Only Class 1 components are considered in this example, but a similar diagram can be prepared for other class components as well.

Austenitic Pipe Inspection Status

As indicated earlier, an evolutionary process brought the ASME Code from the first recognition of its need to today's version. It is expected that this process will continue as improved inspection technology and new fabrication techniques are developed. In fact, the interaction of ASME Code procedures, inspection technology, and fabrication procedure is a dynamic process with each item at one time or another serving as the forcing function for additional change and improvement. Thus, changes in one area usually force at least a review and, in some cases, significant changes in other areas. For example, as improved ultrasonic techniques are developed and proven to have the capability to define precisely flaw location, shape and orientation, it will be necessary to review and alter the standards for judging flaw severity. In this case, the ability to specify precisely will eliminate the need for the simplifying steps now taken with their attendant degree of conservatism used to compensate for the lack of precise knowledge. In turn, this information can be used to generate new more efficient component designs.

Recent experience with the inspection of austenitic piping is a good example of this process in action. In this case, certain pipes in some boiling water reactors developed stress corrosion cracks in service. Because of the suddenness and unexpected nature of these incidents, considerable attention was focused on their cause and possible cures. In-service inspection

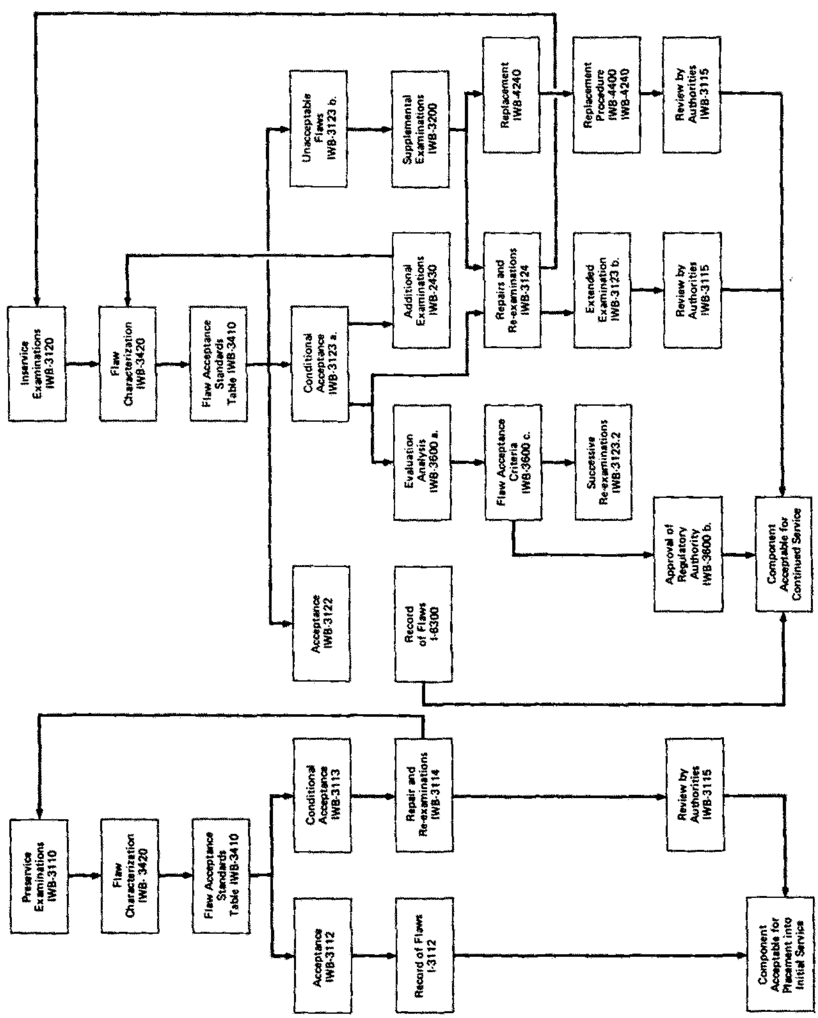

FIG. 1—*Section XI procedures to qualify Class 1 components for service.*

of these lines also received its share of scrutiny. The results of a comprehensive evaluation of the austenitic pipe inspection experience revealed a variety of conditions that hinder performance of an optimum inspection [*11,12*]. These conditions are listed in Table 3. As indicated in the table,

TABLE 3—*Conditions adversely influencing in-service inspection of austenitic pipe.*

Environment
temperature, 40 to 82°C (105 to 180°F)
high humidity
possible high radiation zones
anticontamination clothing required
Design/fabrication
space or access limitations
1000 geometrical reflectors found for each flaw
rough weld crown
counterbore location unknown
counterbore chamfer angle too large
unknown weld root bead contour
variation in weld grain size

the conditions can be divided into two categories. One category (environmental) can be influenced to some degree by the plant owner's action but the overall influence will be an incremental improvement. Also, these items are not physical deterrents to inspection but influence the effectiveness of inspection personnel. The second category (fabrication/design) shows much room for change that will enhance component inspectibility significantly. It is important to note that the performance of in-service inspection on austenitic pipe joints is hampered by many conditions that are generated before the plant becomes operational. These conditions generally have no safety significance but consume valuable time and result in excessive radiation exposure.

Several possible solutions to these problems have been identified. For future plants, these conditions can be reduced or eliminated by considering the inspection requirements in the design, procedure specification, and construction phases. For example, a design generated with an understanding of in-service inspection requirements, at a minimum, should allow adequate access and space to perform the examination. More far-reaching changes such as designing joints for optimum inspectability is also possible and desirable. In the areas of weld preparation and fit-up procedure, changes can be made to reduce the number of geometrical reflectors observed during an ultrasonic inspection such as specifying that the counterbore chamfer angle be less than 9 deg. This would eliminate the problem of ultrasonic energy being mode converted internally into a different propagation mode that can generate ambiguous signals. There is some evidence that use of low heat input welding process would produce a smaller grain size which would be easier to inspect. Finally, the completed weld crown should be of such a contour to allow an ultrasonic search unit to be passed over it.

For existing plants, removal of the weld crown will improve inspectability. However, the significant gains will result from development of new or improved inspection methods. Several possibilities have been identified and include: standardization of inspection equipment, better ultrasonic signal processing techniques, improved data display and recording methods, as well as potential alternatives to the ultrasonic technique now used. Concepts in the latter category include X-ray tomography, eddy current inspection, ultrasonic interferometric holography, image enhancement, and acoustic emission.

Considerable work is already underway to develop improved inspection methods and more work is expected to be initiated in this area as well as in the welding processes (and procedures) and fit-up specifications. Through these combined efforts, solutions should result that will permit improved inspection ability with a high degree of reproducibility.

Changes in Section XI also need consideration. One suggestion is to replace the complete volumetric inspection requirement of pipe with one that permits concentration on the inner and outer one-third of the wall thickness. The proposed elimination of inspection of the center one-third of the wall is based on the fact that almost invariably all cracks originate on the inside-diameter or outside-diameter surface. Thus, inspection of this central region is not expected to produce much benefit but will cause considerable extra time and radiation exposure.

The austenitic pipe inspection situation being faced today is a good illustration of the "push-pull" factors at work in Section XI development. In this case, the requirements for the inspection are stipulated, but no examination procedure is specified because the people responsible for code development recognized the limitations and problems listed in Table 3. As a consequence, the Appendix III procedures for pipe inspection are mandatory only for ferritic piping and are optional for austenitic material. To make the procedure mandatory for austenitic piping easily could mandate requirements that present technology cannot meet. If this happens, a legal requirement would exist that could not be fulfilled and this would compromise the intent of Section XI. By making the procedure optional, it is expected that it will be used as guidance and provide valuable in-service experience. This experience combined with the results expected from new inspection development programs and fabrication changes will be used to develop a workable mandatory inspection procedure. For this particular case (and probably true in the general case), it is evident that a system much more amenable to inspection results from the consideration of stipulated in-service inspection requirements during all phases from design through operation.

The primary result from the use of the Section XI is the additional confidence in the system's structural integrity. There are other benefits—the experience gained by in-service inspection can guide the plant designers toward improvements in the design, construction, and quality standards incorporated into new nuclear power plants. In addition, the results provide assurance to regulatory authorities that the safety margins applied in the design stage are adequate and can be maintained throughout the service lifetime of the nuclear power plant. Schematically, the interaction of Section XI requirements, product life cycle, and results gained from an in-service inspection are shown in Fig. 2.

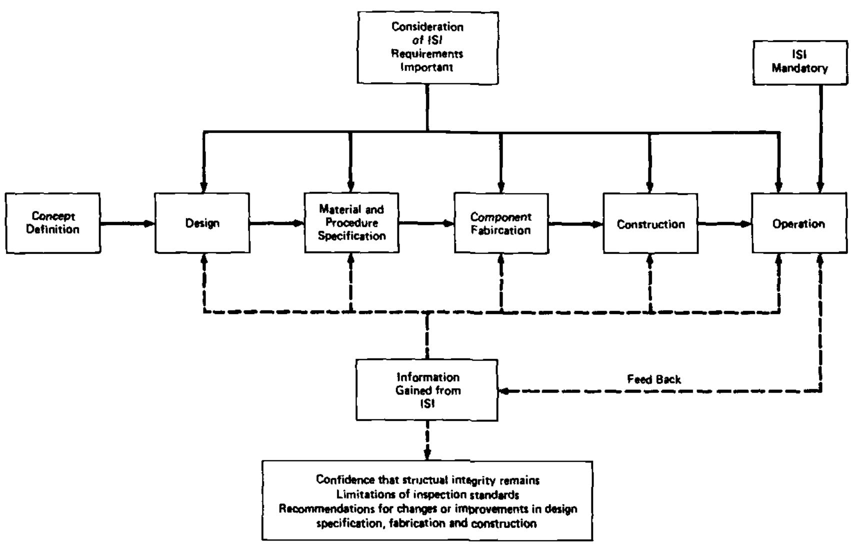

FIG. 2—*Diagram showing the interation between inspection requirements and results with the stages in a product cycle.*

Manpower and Qualification

The mandatory nature of the ASME Code combined with the specificity of examination precedures and the need to make judgments on flaw severity means that highly skilled people knowledgeable in both the examination technology as well as Section XI requirements must be available. The availability of people with these abilities is limited. This fact, coupled with the growing number of nuclear power plants and the slow expansion of qualified manpower, may result in a shortage of adequately trained people to conduct in-service examinations. Under these conditions, care must be taken to assure that the examinations are conducted by competent people. Considerable debate is underway in the nuclear industry and in the nondestructive examination profession as to the optimum way to meet this challenge. The approach that the author favors involves a two-part certification process. First, the person would be required to satisfy a basic certification of competence. Such a certification could be administered to an appropriate national standard common for all industries. The second step would require specific certification of competence for a particular industry or job. In this way, there is added assurance that people will possess the same general level of competence and be knowledgeable with regard to the conditions and requirements encountered during in-service inspection of a nuclear power plant. If this proposal were put into effect, it would help assure that the people involved in in-service inspection were qualified. However, it does not address the problem of having adequate manpower to certify. To accomplish this goal, efforts must be made to motivate the academic community to take a more active role in providing the basic training needed for people interested in all facets of nondestructive examination.

Summary

In one decade, the nuclear industry has changed its philosophy from that of no periodic inspection of components to one of a well specified periodic examination requirements documented in the ASME Code, Section XI, "Rules for Inservice Inspection of Nuclear Power Plant Components." This document describes the legally required examination in terms of frequency, components to be inspected, examination procedure, standards for flaw signal evaluation, flaw analysis, and repair procedures. Section XI is evolutionary in nature with complete requirements specified now for those components with the greatest safety significance. Requirements for the remaining components are under development. When these activities are completed, Section XI will encompass almost all areas of a nuclear power station once it becomes operational.

The evolution of Section XI is characterized by a dynamic process that is still underway. Inspection of austenitic piping provides a current example of the interaction of inspection technology, fabrication procedures, and code intent that must be considered for development of an effective and workable inspection requirement.

More effort is needed to assure that adequately qualified people are available to conduct in-service inspections because the examinations require people skilled in nondestructive examination technology and knowledgeable in ASME Code requirements.

Acknowledgments

It is a pleasure to express my appreciation to S. H. Bush for the time he made available from a very busy schedule to review this material. I also wish to acknowledge the assistance given by my colleagues K. E. Stahlkopf, R. E. Smith, and T. U. Marston.

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F. C. Berry[1]

ASNT Recommended Practice for Nondestructive Testing Personnel Qualification and Certification (SNT-TC-1A) and Its Use

REFERENCE: Berry, F. C., "**ASNT Recommended Practice for Nondestructive Testing Personnel Qualification and Certification (SNT-TC-1A) and Its Use,**" *Nondestructive Testing Standards—A Review, ASTM STP 624*, Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 53–62.

ABSTRACT: The need for standardization of nondestructive testing personnel qualifications brought about the writing of the American Society for Nondestructive Testing (ASNT) Recommended Practice for Nondestructive Testing Personnel Qualification and Certification (SNT-TC-1A). The choice of an organization to prepare such a document was based on ASNT's prime interest and its membership being a cross-section representation of industry and government organizations within the United States.

ASNT Recommended Practice SNT-TC-1A is a combination of various requirements taken from American government and industry specifications. This document is designed to be adapted by any user to fit a specific need.

ASNT offers an additional service of review or examination of personnel for the qualification as a Level III Nondestructive Testing person.

KEY WORDS: nondestructive testing, standards, qualifications, documentation, certification, code requirements, written tests

In October 1966, the American Society for Nondestructive Testing (ASNT) published a document entitled Recommended Practice for Nondestructive Testing Personnel Qualification and Certification (SNT-TC-1A). The lettering on this document was based on ASNT's name at that time, "S" for Society, "N" for Nondestructive, and "T" for Testing. The training was "T," certification "C" and 1A was the first document published by ASNT on this subject. Since its first publication as a recommended practice for personnel qualification and certification, many other organizations have accepted it for their use.

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Within the last decade, nondestructive testing (NDT) in all its increased complexity has become a mandatory tool of industry. Customers use NDT to ensure receiving what they have specified. Reliability requirements of NDT have made it necessary for those performing NDT's to be trained specifically and qualified for their tasks.

In the late 1950s, government, prime contractors, and fabricators wrote specifications with requirements for training and qualification of nondestructive personnel. Such specifications varied widely among the different writers. Suppliers on whom these specifications were imposed contractually found themselves involved in a variety of requirements as well as numerous audits. Meeting specifications was a common requirement of all concerned. Government and industry alike felt the need to establish standard guidelines for training and certification. A competent group to establish these guidelines was solicited by those with the common need. In 1961, ASNT, through its Technical Council, assigned a Task Group to study feasibility and preparations of a document to meet the need. In October 1966, the Personnel Qualification Division of the Technical Council generated and published the original ASNT Recommended Practice SNT-TC-1A.

ASNT Recommended Practice SNT-TC-1A was written in such a manner that any user could adapt it to his specific requirements. In time, the document was applied voluntarily by many manufacturers and suppliers as their method of qualifying and certifying personnel. In 1968, ASNT Recommended Practice SNT-TC-1A was incorporated into the American Society of Mechanical Engineers *(ASME) Boiler and Pressure Vessel Code.* Many users intending to meet code requirements made the common error of referring to their personnel as being qualified in accordance with ASNT Recommended Practice SNT-TC-1A without full knowledge of the document's recommendations. Reference to the document as a strict specification led to many errors of interpretation. The key to ASNT Recommended Practice SNT-TC-1A as a usable document is in Paragraph 5, which instructs the user as follows:

5. Written Practice

5.1 The employer shall establish a written practice for the control and administration of NDT personnel training, examination, and certification.

5.2 The employer's written practice should reflect the guidelines referenced in Para. 1.

5.3 The employer's written practice shall describe the responsibility of each level of certification for determining the acceptability of materials or components in accordance with the applicable quality standards.

The original ASNT Recommended Practice SNT-TC-1A was published in October 1966 and was not revised except editorially until June 1975. The June 1975 revision took into account all of the problems with interpretation of various paragraphs throughout the document, and an effort was made to clarify all areas where it was necessary.

The June 1975 ASNT Recommended Practice SNT-TC-1A is for the qualification and certification of nondestructive testing personnel. It provides a format that industry can follow in writing procedures for the qualification and certification of personnel which meet the needs and requirements unique to each segment of industry.

The document contains recommended practices for personnel qualification and certification by employers in the following nondestructive methods: radiography (RT), ultrasonic (UT), eddy current (ET), leak testing (LT), magnetic particle (MT), liquid penetrant (PT), and neutron radiography (NRT). Also included are recommended education, experience, and training requirements for the different testing methods. Supplementary documents currently available include: radiography (1971), ultrasonics (1971), eddy current (1968), magnetic particle (1971), and liquid penetrant (1968).

New publications containing questions and answers for each of the seven methods listed in the June 1975 edition of ASNT Recommended Practice SNT-TC-1A are in preparation. Until these are published, the questions and answers in these five documents are valid and available for use.

Documentation of Certification in a Particular Procedure

The point to remember here is the procedure, as written by any user of this document to satisfy the requirements of his company and be acceptable to his customer, should follow the recommendations contained in Paragraph 5 (stated earlier in the paper).

Certification will be as per Section 9.

9. Certification

9.1 Certification of all levels of NDT personnel is the responsibility of the employer.

9.2 Each employer shall establish written practices covering all phases of certification including training as specified in Para. 5.

9.3 Certification of NDT personnel shall be based on demonstration of satisfactory qualification as determined by procedures outlined in Para. 6, 7, and 8 as modified by the employer's written practices.

9.4 At the option of the employer, an outside agency may be engaged to provide NDT Level III services. In such instances, the responsibility of certification must be retained by the employer utilizing outside services.

9.5 The purchaser of outside certification services is responsible for auditing the agency providing such services to assure that training, examination, and certification are in accordance with this document. He must maintain a written record of his audit.

9.6 Certification records shall be maintained on file by the employer and should contain personnel records of the certified individuals and copies of written practices as required by Para. 5.

9.6.1 The personnel records of the certified individuals should include as a minimum the following:

a. Name of certified individual.
b. Level of certification and test method.
c. Educational background and experience of certified individuals.
d. Statement indicating satisfactory completion of training in accordance with the employer's written procedure.
e. Results of the physical examination prescribed in Para. 8.2.a.
f. Copies of current examinations and of grades for all previous examinations and descriptions of practical test objects.
g. Percentile weights assigned to each examination if examinations were employed for qualification.
h. Composite grade if examinations were employed.
i. Date of certification and/or recertification and the dates of hire or assignment to NDT.
j. Signature of certifying agency representative.

9.7 Re-Certification

9.7.1 All levels of NDT personnel should be re-certified at least once every three years in accordance with one of the following criteria as determined by the employer:

a. Evidence of continuing satisfactory performance.
b. Re-examination in accordance with Para. 8 and 9.

9.7.2 NDT Personnel may be re-examined any time at the discretion of the employer and have their certification extended or revoked.

9.7.3 The employer shall in his written practice establish rules covering the duration of interrupted services which will require re-examination and re-certification.

The employer may employ persons previously trained and certify them in accordance with Paragraph 10.

10. Termination

10.1 All certifications shall be automatically terminated when an employee leaves the employer where he had been certified.

10.2 A terminated Level I or II employee may be re-certified to his former NDT level by a new employer based on examination as described in Para. 8.2 provided all of the following conditions are met to the new employer's satisfaction:

a. The employee has proof of prior certification.
b. The employee was working in the capacity to which he had been certified within six months of his termination.
c. The employee is being re-certified within six months of his termination.

It is intended that a *qualified individual* who is a certified Level III select from the list of questions provided or write questions and conduct an examination of employees under his supervision to ascertain that they have understood the training material in accordance with Paragraph 8.

This procedure is for the certification by the *employer.* ASNT currently is developing a supplemental program for certification of Level III personnel. This service will be offered and publicized upon the approval of the ASNT Board of Directors of a Level III plan.

Questions related to the use of June 1975 ASNT Recommended Practice SNT-TC-1A are to be referred to the Technical Director, ASNT, 3200 Riverside Drive, Columbus, Ohio. When requested, formal answers will be made in writing to the inquirer with copies to the applicable code and standard groups. Clarifications in the use of ASNT Recommended Practice SNT-TC-1A will be published periodically in *Materials Evaluation.*

From the inception of the ASNT Personnel Qualification and Certification Program, first adopted and published in 1966, the Level III individual was intended to be the key to the complete program.

A Level III individual, by the ASNT concept, was expected to have the necessary experience, education, and background to establish the program for any company's nondestructive testing needs. ASNT Recommended Practice SNT-TC-1A was established as a reasonable guideline to assist a competent individual in establishing such a program. This requirement is stated clearly in Paragraph 5 of the original document.

The capabilities of a Level III individual, as outlined in ASNT Recommended Practice SNT-TC-1A, have not changed appreciably since the original publication in 1966. The original paragraph reads as follows:

> NDT Level III—An NDT Level III individual shall be capable of establishing techniques, interpreting specifications and codes, designating the particular test methods and techniques to be used, and interpreting the results. He shall be capable of evaluating results not only in terms of existing codes or specifications, but also shall have sufficient practical background and applicable material technology to assist in establishing test and acceptance criteria where none are otherwise available. It is desirable that he have general familiarity with all other commonly used NDT methods. He shall be responsible for conducting examinations of NDT Level I and NDT Level II personnel.

The new edition of ASTN Recommended Practice SNT-TC-1A, issued in June 1975, has been revised to read as follows:

> NDT Level III—An NDT Level III individual shall be capable of and responsible for establishing techniques; interpreting codes, standards and specifications; and designating the particular test method and technique to be used. He shall be responsible for the complete NDT operation he is qualified for and assigned to, and shall be capable of evaluating results in

> terms of existing codes, standards, and specifications. He shall have sufficient practical background and applicable materials, fabrication and/or production technology to establish techniques and to assist the design engineer in establishing acceptance criteria where none are otherwise available. It is desirable that he have general familiarity with other commonly used NDT methods. He shall be responsible for the training and examination of NDT Level I and Level II personnel for certification. The actual administration of training and grading of examinations may be designated to the duly selected representative of the Level III individual and so recorded.

Misuse of ASNT Recommended Practice SNT-TC-1A in this particular area has been one of the main objections to its application. Most of the misuse has been by employers in certification of Level III individuals with inadequate documentation of education, experience, and training background of the individuals they have certified. Use of ASNT Recommended Practice SNT-TC-1A to establish Level III individuals by decree, anointment, or appointment without properly documenting training, education, and experience is contrary to the intent of ASNT Recommended Practice SNT-TC-1A in all respects.

ASNT has no power to police the use of ASNT Recommended Practice SNT-TC-1A; however, in an effort to reduce the Level III problem, ASNT has struggled to develop solutions for more than five years. At the 1974 Fall Conference of ASNT, the Board of Directors voted to implement a program for certification of Level III personnel. Following the ASNT Recommended Practice SNT-TC-1A concept, the Level III will be responsible for his company's Level I and Level II NDT personnel. The decision of ASNT was to avoid any indications that they would become involved in certification of Level I and Level II NDT personnel. The Board of Directors of ASNT voted to certify only Level III personnel on a voluntary basis.

Certification by ASNT of Level III personnel, after many hours of discussion, argument, and deliberation, has been deemed appropriate. The certification by ASNT of Level III will be for records of educational achievements, nondestructive testing experience, and either passing an examination or presenting for review by a select panel evidence of qualification acceptable to a set standard for grandfathering.

The plan of ASNT to assist all industry by certifying competent NDT Level III personnel for their use is expressed in an article written by the former President of ASNT, C. E. Lautzenheiser, and published in the May 1976 issue of *Material Evaluation*:

> Certification in accordance with the guidelines of SNT-TC-1A indicates that an *employer* has made a review of the individual's qualifications and has accepted the responsibility for the Level III activity of the person within the employer's organization. It is very important to note that the word "Certifica-

tion" indicates a record of achievement and/or qualification, in one case, and an acceptance of responsibility by management in the other case. Also, even though an employer uses ASNT services he can and probably will apply a specific examination requirement to insure that the Level III person is technically competent in the employer's specific requirements. The major criticisms that have been leveled against SNT-TC-1A are that the requirements for a Level III individual are not definitive and that the individual can be certified without examination.

The intent of the ASNT program is to establish minimum standards for Level III personnel in each NDT discipline. It would be virtually impossible for any organization to establish and administer a Level III program in which a person could be qualified in the requirements of all industrial applications. Therefore, it is still the responsibility of the employer to apply whatever specific examination requirements he deems necessary before certifying the individual in accordance with ASNT Recommended Practice SNT-TC-1A.

The Board of Directors of ASNT has been grappling with this problem for more than ten years, and the reader can be assured that the views and opinions of many organizations and individuals have been considered and factored into the program. It is also a certainty that if ASNT does not establish such a program, programs will be established by other organizations over which ASNT has no control. This is one reason for the Board action, and another equally important reason is the desire to improve the professional image of ASNT, which was the primary goal established in the first Goals Conference in 1973. In implementing this program, ASNT is following the actions of many other major technical societies that certify personnel within the individual society's expertise. Examples of that are certification of Corrosion Specialists, Quality Engineers, and Manufacturing Engineers.

With this background, the following actions are under way. In the April 1976 newsletter is a summary of actions authorized by the ASNT Board of Directors. A permanent committee has been established, responsible to the Board, to establish necessary policies and procedures for the Level III Certification Program. This committee, like all other standing committees, is chaired by a member of the Board, is responsible to the Board, and its actions require Board approval. The committee members were chosen carefully to represent diverse segments of industry and education. This committee held an organization and planning meeting during the Spring Conference and another meeting in early May. The principal tasks facing this committee are finalizing the procedures for Level III Certification by examination and maintaining the program in the future. Also, it must decide on answers for these important questions: how often should individuals require recertification, and what are the requirements for recertification?

The most immediate action under this program is to establish a Review Board and to start accepting and processing applications for Level III certification. The first Review Board is hoped to be in operation by mid-summer, but not later than 1 Sept. 1976. Although much activity is involved in getting organized, the first concrete action that is planned is to have the Review Board act on applications of volunteers from the Board of Directors. This will serve as a tryout of the program. The requirements for Level III Certification without examination are quite stringent, and, therefore, Review Board members must be of an even higher caliber. For example, some of the requirements for a Review Board member are 20-years experience in NDT, competence in more than one NDT discipline, and management experience. It has been quite difficult to find Review Board members with the required qualifications who also would be backed by their companies for the necessary travel and meetings.

The Board of Directors established a time limit of six months for accepting applications for Level III Certification without examination; the six-month period will start after a suitable information program has reached potential candidates through our media and the media of related organizations.

It is obvious that there is great interest in what the requirements for Level III without examination are and when the application forms will become available. The first part of this is relatively easy to answer. The requirements for Level III Certification without examination are summarized as follows:

Experience Requirements for Certification without Examination

The basic requirements are that the applicant must furnish evidence of a High School education or equivalent and have a minimum of fifteen years of progressive qualifying experience. This experience may apply to one or more methods of NDT simultaneously by determination of the Review Board and based upon the applicant's submitted experience record. Certain professional and educational attainments (limited to only one of those listed below) can be substituted for experience as follows:

Six years' maximum credit for Professional Engineering Registration in any state.

Five years' maximum credit for a Bachelor of Science or higher degree in Engineering, Science, or Physics.

Four years' maximum credit for successful completion of an Engineer-in-Training written examination in any state.

Three years' maximum credit for a Baccalaureate Degree from a College or University curriculum of a technological nature.

One-year credit for each full year successfully completed in an Engineering or Science curriculum in a University, College, Post-Secondary Vocational, or Technical School with a maximum of two years' total credit.

One-year credit for each full year successfully completed in a Vocational or Technical School offering a curriculum in Nondestructive Testing. Successful completion of a two-year curriculum in Nondestructive Testing may gain an additional one-year credit.

Four years' maximum credit for teaching Nondestructive Testing in a University, College, Vocational, or Technical School.

Four years' maximum credit for teaching or developing courses for commercial organizations.

References Required

At least four references are required; it is desirable but not mandatory that the individuals selected as references be ASNT Fellows or Registered Professional Engineers. At least two must have nondestructive testing experience and have direct knowledge of the applicant's professional character and accomplishments.

Code of Ethics

Applicants must acknowledge and abide by a separate Code of Ethics if certified by ASNT. Failure to do so can be grounds for revocation of certification.

Fees

The maximum fees for certification without examination will be $60.00 for the first NDT method in which an applicant seeks certification, and $15.00 for each additional method.

Application

Applications for certification are now available upon request from ASNT Headquarters.

In summation, the following actions were taken by the Board of Directors with regard to certification:

1. Approved a Level III Grandfathering program as developed by the Ad Hoc Select Committee. This program will certify that presented evidence of education, training, and experience meets or exceeds minimum standards established by the Society.
2. Affirmed that this certification is not that stated in SNT-TC-1A.
3. Affirmed that Certification Programs for Level I and Level II personnel are not being considered.
4. Authorized immediate establishment of a program for Level III Certification without examination with a starting date of September 1 at the latest.
5. Established a six month time period for acceptance of applications for certification without examination.
6. Approved membership of the Standing Committee for Level III Training and Certification.

The program described here is offered to industry for its use on a voluntary basis. Regardless of whether the Level III individual is certified by ASNT or by the employer, successful implementation is still dependent upon the Level III as the key individual.

A small company or a large company with a small NDT operation requiring a simple NDT program may need an entirely different qualification program for its Level III personnel than the more complex needs of a company or industry requiring NDT to its maximum capabilities. The smaller company, for example, may have an operation that is confined to no more than one or two NDT methods. These methods may only be applicable to the product using simple procedures. This type of operation requires a lesser degree of training and experience than a more complex operation.

The more complex operation may involve four, five, or more NDT methods being pushed to their limits for controlling quality and providing NDT results. Where NDT is in such demand the qualification and certification program for Level I and II personnel must be designed to assure that personnel performing the NDT work are qualified. In either case, a Level III individual is needed to establish the NDT personnel qualification and certification program for his company using ASNT Recommended Practice SNT-TC-1A as it was intended originally to be used and is stated at the beginning of this paper.

The only policing power for the correct use of ASNT Recommended Practice SNT-TC-1A remains with the purchaser. NDT services are now very much a part of contractual obligations. The vendor surveillance program is geared to audit the programs outlined by the Level III individuals to cover NDT personnel. The customer, through his surveillance of the supplier, ensures that the Level III individual is providing the NDT services required by the purchaser's specification.

The success or failure of the ASNT certification program or any other certification program will depend upon joint acceptance by both producer and consumer.

J. K. Aman[1]

Overview—Radiographic Nondestructive Testing Standards

REFERENCE: Aman, J. K., "**Overview—Radiographic Nondestructive Testing Standards,**" *Nondestructive Testing Standards, ASTM STP 624,* Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 63-73.

ABSTRACT: This paper is an overview of the standards in the field of nondestructive testing (NDT) radiography. The objective is to lay the overall framework and direction for more detailed coverage to follow. First, the NDT radiographic system variables are discussed in an effort to point out the need for increased standards activity. This activity should produce better precision in radiographic testing.

A framework of achieving the requisite precision at minimum cost is presented. This framework interrelates radiographic personnel, procedure, equipment and supplies, producing repeatable radiographs. The framework calls for controlling the system, which requires image quality indicators (IQIs) and adequate assurance as to requisite permanence of the radiograph.

The present status and future needs in standardization in each of the areas mentioned is covered. This includes a table of the standards and present activity on each of them.

NDT radiography is a flexible tool. The paper concludes with the challenge of building a more precise radiographic structure.

KEY WORDS: nondestructive testing, standards, radiography

The objective of this overview paper on radiographic nondestructive testing (NDT) standards is to present the status of these standards, some of the problems with the standards, and the work that is being done presently to solve these problems. Another objective is to show where and how the elements of the standards program fit into the total objective of making radiography a more precise technique, and what trends and needs are developing for the future. The priority issue then is to improve the test precision. Of equal priority is improving the precision at minimum or even reduced cost.

[1]Product manager, E. I. du Pont de Nemours and Company, Inc., Wilmington, Del. 19898.

Test Variables

If tests are not repeatable and lack precision, where do we look for improvement? First, consider all the variables in the radiographic NDT system. Figure 1 lists the variables that affect test sensitivity and, in turn, reliability. In radiography, we have some level of quality assurance represented by the image quality indicator (IQI) or penetrameter on the film. Figure 1 breaks the image of the IQI into resolution and contrast, where resolution is the ability of the test to show very high frequency detail, and contrast is the ability to show small changes in radio opacity.

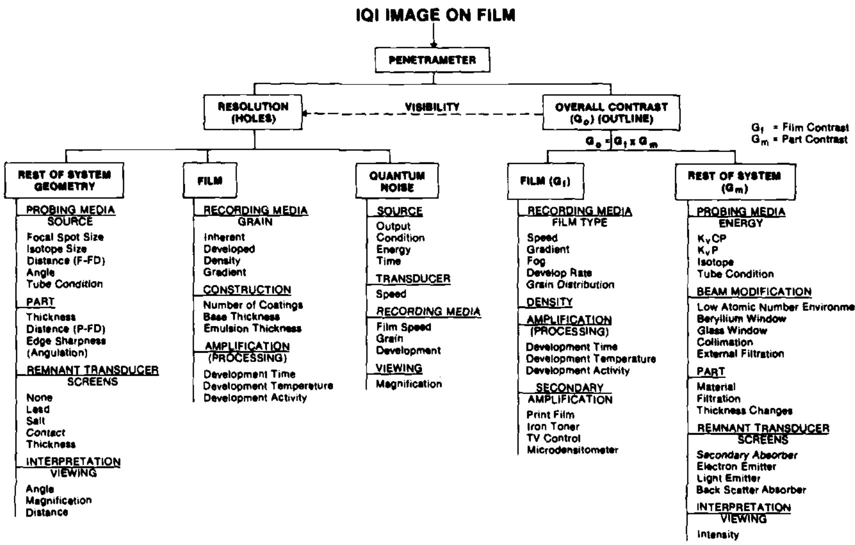

FIG. 1—*Variables that affect radiographic image quality.*

Considering contrast first, overall contrast is divided into parts of the film and of the part. Part contrast is controlled by the rest of the system other than film, that is, kilovolt (energy of X-ray), isotope energy, inherent and external filtration, part thickness and opacity, control of secondary radiations, and viewing conditions. They must be controlled and repeatable, if a precise, reliable part contrast is to be obtained.

Consider the opportunities for nonrepeatability in these variables:

kVp/kVcp	circuitry, tube conditions, inherent filtration, line voltage
mA tube current	meter not direct reading, circuitry, tube design and age, line current
external filtration	screen, cones, diaphragms, tube port
screens as transducers	light emission, screen thickness, and variations

In the column for film contrast, major variables controlling contrast are density, extent of development, film speed, and secondary methods for enhancing contrast.

There is more opportunity here for intended or unintended changes in film contrast:

density	exposure, development (contrast higher with higher density)
film speed	higher contrast with slower speed
extent of development	change in time, temperature, and activity
secondary methods of contrast	controls on multification factor

Overall contrast (the contrast observed on the final radiograph) is the product of part and film contrast and affected by all the mentioned variables.

Moving to the resolution side of Fig. 1, there are three main areas affecting resolution: unsharpness caused by film, unsharpness caused by the rest of the system (or geometric unsharpness, Ug), and lack of resolution caused by having too few X-ray photons forming the image (quantum noise).

Major considerations in geometric unsharpness are source size (or effective source size), screen contact, edge sharpness (of the detail to be resolved), and part-to-film distance. To illustrate problems arising from just one of these, consider the illustration (Fig. 2) of how the focal spot of an X-ray tube varies as your vantage point moves around on the film plane.

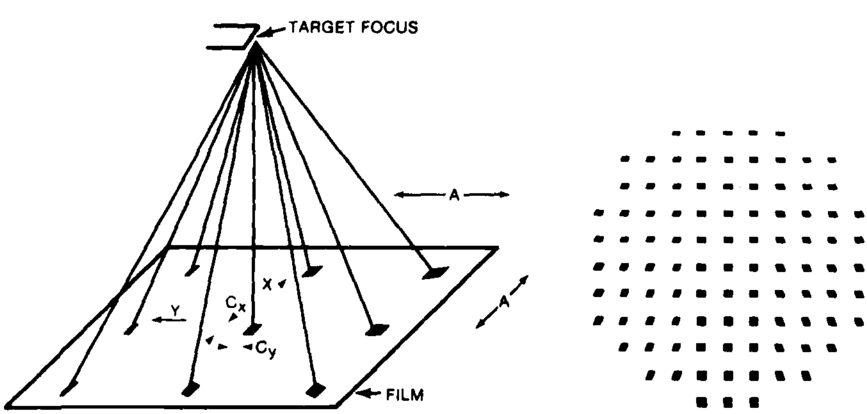

FIG. 3—*Radiographic standards framework.*

In addition, the intended or unintended changes in geometric unsharpness are caused by:

part edge sharpness	various angles of edge to radiation ray
screen contact	air entrapment between screen and film
part to film distance	positioning of part and film

Film unsharpness is controlled in the construction and manufacture of film. Figure 1, again, lists the items that are controlling.

Resolution also is affected by quantum noise. This subject easily could take a full paper in itself as most radiographers are unfamiliar with its effect on image quality. Simply, it is, in industrial radiography, almost equal to what generally is known as "grain." It is the density fluctuation caused by increasing or decreasing the number of X-ray photons used to produce the radiographic image. It varies in direct proportion with the speed of the recording media, which, in turn, is a function of energy level, screen, film grain size, and development. Again, the variables and their intended or unintended change will affect test sensitivity and variability.

We have considered the radiographic system in outline form. Our challenge appears simple; we standardize each elemental variable, and the total system becomes more precise. As it is impossible to cover all the variables in our allotted time, we have chosen to cover the following papers appearing elsewhere in this publication.[2]

"Radiographic Equipment Calibrations" by Elmer Eisenhower

"Neutron Radiography" by Jerry Haskins

"IQI's" by Arnold Greene

"Film/Processing Systems Classification" by Dan Polansky

"Real Time Imaging and Gaging" by Bill McKee

"Reference Radiograph" by Sol Goldspiel

But, before getting into their details and with an appreciation for the variables that must be controlled for precision radiography, let us take a look, in a general way, at where we stand with our present standardization efforts and what our needs are for the future.

First, please allow for a digression. There may be some pragmatic NDTers who are saying at this point that we are overregulated already. "Any attempt," they might say, "to improve precision is just going to increase the test cost." This is not necessarily true. Standardization through easier communication and, hopefully, increased repeatability can help to lower cost.

In any case, our objective in standardization should be "to provide the requisite precision at a minimum cost (not price)." In addition to the cost objective, I agree wholeheartedly with Bob McClung, when he said, "Documentation (standardization) should not inhibit intelligent innovation and improvements.[3]

Overall Radiographic Standards Framework

To review present status and future development of standards, we sug-

[2]McClung, R., "Into the Looking Glass," American Society of Nondestructive Testing, Lester Honor Lecture, 1974.

[3]See Contents for page numbers.

gest using the flow diagram shown in Fig. 3. Here again, the objective is shown—to provide the radiographic NDT customer with the requisite precision at minimum cost. Standards of acceptance include flaw accepta-

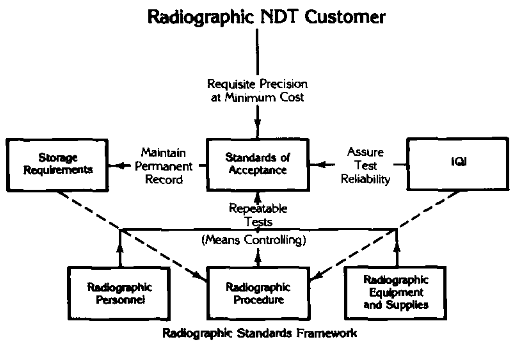

FIG. 2—*Effective focal spot as viewed from various points on the film plane.*

bility as well as radiographic physical and image quality. The IQI image provides quality assurance of test sensitivity. The major areas for standardization that feed into the test are personnel, procedure, and equipment and supplies. In addition to the test itself, as some product life cycles lengthen, we are questioned more on the need to assure the keeping quality of the radiographs for as much as 40 years.

Present Status and Future Needs in Radiographic Standards

Refer to Table 1 for the remaining discussion.

Acceptance Standards

Acceptance standards are found in many places, and we do not plan coverage of all of them. Goldspiel will be covering one aspect of standards acceptance criterion in his coverage of ASTM reference radiographs elsewhere in this book. The American Society of Mechanical Engineers (*ASME*) *Boiler and Pressure Vessel Code* has some flaw acceptance criteria, but, interestingly, it also has requirements on the physical quality of radiographs; radiographs shall be without artifacts. The "in topic" in acceptance standards these days is fracture mechanics. Perhaps this is the strongest argument for more precision (meaning perhaps higher sensitivity) in radiography because it requires not only determination of flaw size but also the size of the largest undetected flaw. Radiography (at

TABLE 1—*Radiographic standards, present status and future needs, summary.*

	Present	Future
Acceptance Standards	ASTM Reference Radiographs *ASME Boiler and Pressure Vessel Code*	flaw quantification
IQI	ASTM Method E 142-72 MIL-STD-453 MIL-STD-271 NASA MSFC-355B	U.S. standard plaque IQI finer tuned quality levels unsharpness meter (CERL) neutron and real time common wire/plaque standard
Personnel	ASNT Recommended Practice SNT-TC 1A Supplement A—X and Gamma Ray Supplement D—Neutrons 0.453 and 271	Level III exam
Procedure	ASTM Method E 94-68 (1974) API-1104 company standards P & W XRM-IP	processing control screen technology thickness fluorescent (with Type 1 and 2 films)
Equipment and materials	American National Standard PH 2.8-1975 (HVL and film sensitometry) NBS HFE (100 kV), HFG (150 kV), HFI (220 kV) (Dosimeter calibration) P & W MCL 017 American National Standard N43-7 (radiation safety of X-ray equipment) NBS Density (0–4) SRM 1001	ASTM Method E 94-68 (1974) Table II Film/Processing System Classification Calibration of: kV—HVL energy and variability mA—roentgens output and variability focal spot size lead screens
Records maintenance	American National Standard 1.41-1973 P & W XRM-1P	ASTM Method E 94-68 (1974) to include definitive storage recommendations

NOTE—

American Petroleum Institute Standard for Welding Pipe Lines and Related Facilities (API-1104)

American Society for Testing and Materials Controlling Quality of Radiographic Testing (E 142-72)

National Aeronautics and Space Administration Standard Radiographic Inspection of Electronic Parts (MSFC-355B)

U.S. Air Force Military Standard on Inspection, Radiographic (MIL-STD-453A)

U.S. Navy Military Standard on Nondestructive Testing Requirements for Metals (MIL-STD-271E) least 2-2T radiography) appears to be behind the other NDT methods in this field. More communication is needed on what is being done in this field with radiography.

Image Quality Indicators

Our present IQI (penetrameter) is in at least four different standards. When using the usually specified single penetrameter per thickness they are based on test sensitivity steps (quality levels) of approximately 40 percent. There are many variations of plaque-type IQI. A first step is to come to a common U.S. plaque-type penetramteer. Greene's paper will cover the American Society for Testing and Materials (ASTM) Subcommittee E07.01 on Radiographic Practice and Penetrameters' effort to do just that.

Also, perhaps an optional system of an increased number of quality levels would help reduce the pressure to specify each and every step in the radiographic procedure. Our use of wire penetrameters presently is restricted to the electronics field. Perhaps we need a correlation standard or a standard U.S. wire-type penetrameter or both. The field of neutron radiography needs an IQI, and ASTM Subcommittee E07.05 on Neutron Radiography, which you will be hearing about later from Haskins, is hard at work to produce that standard.

Radiographic Personnel

Personnel qualification is being handled by the American Society for Nondestructive Testing (ASNT). To date, the field of radiography is represented in two supplements to ASNT Recommended Practice on Personnel Qualification (SNT-TC 1A), Supplement A on radiography and Supplement G on neutron radiography, which has been issued just recently. Our most pressing need in personnel qualification (and certification) is the better definition of Level III requirements. And, as indicated in Berrys' paper, ASNT is hard at work accomplishing that.

Radiographic Procedure

Here, ASTM Recommended Practice for Radiographic Testing (E 94-68 (1974)) is the most mentioned standard, but those standards listed under IQIs in Table 1 also contain procedural requirements. The procedure of doing radiography varies greatly with the end use of test. ASTM Recommended Practice E 94-68(1974) covers only film X and gamma radiography. McKee will cover the need for real time imaging and gaging, and Haskins will discuss the need for a recommended practice in neutron radiography. Exposure techniques now are covered in suggesting records (charts, etc.) to keep track of various part numbers, material, thickness, X-ray machine, etc. With calibration (discussion under equipment and supplies), techniques will be able to be recommended more precisely with X-ray energy specified in half value layer (HVL) and exposure in roentgens (instead of milliampere minutes).

When considering the variables having an effect on image quality, more radiographers are coming to realize the need for monitoring and controlling processing. Recommended processing procedures in ASTM Recommended Practice E 94-68 (1974) are receiving attention. The section on automatic processing will be rewritten. Screens, both metallic and fluorescent, are receiving a new look. Screen contact requirements and use of fluorescent screens with Type 1 and 2 film need to be clarified in the standards. Procedural standards should take a new look at records retention, and this is discussed later in this paper.

Radiographic Equipment and Material

The average radiographer, engineer, or manager generally is not aware of standards that exist in this area. Recently, the American National Standards Institute (ASNI) Committee PH 2-34 on Photographic Material issued a revision to Method for the Sensitometry of Industrial X-ray Films up to Three Million Electron Volts (PH 2.8-1975) of the sensitometry of industrial X-ray film. I am sure that Polansky will cover this standard later in more detail in the discussion of film classification. This standard, in addition to giving focal points for speed and gradient calculation using an H & D curve, specifies four energy levels of radiation in HVL:

	HVL	With Filter
100 kV	1.0 mm	2-mm copper
200 kV	3.5 mm	8 mm copper
Ir 192	...	8-mm copper
Co 60	...	none

(HVL is not needed for the consistent energy emission of iridium 192 and cobalt 60.) And, exposure is specified to be expressed in roentgens, not milliampere minutes.

Now, this brings us to one need in the area of X-ray equipment. Eisenhower will cover this in detail in his paper. Consider that we use kilovolts as energy of X-ray, when, in fact, tube design and machine circuitry can produce quite different energy at the same kilovolt. As an extreme example, consider a beryllium window half-wave machine and a glass window constant potential operating at 90 kV. If the constant potential were expressed in terms of the half-wave machine, its kilovoltage would be approximately 115. These two X-ray machines operating at 90 kV would yield radiographs of considerably different contrast. The output, quantity of X-ray in roentgens, also would be quite different and would not be characterized accurately by the milliampere reading of the machine. Using ANSI specification of HVL for a given kilovolt, I believe we need to calibrate kilovoltage to reflect X-ray energy in terms of HVL. And equally, milliamperage should be calibrated to read roentgens output. Percent variability should be a matter of manufacturer specification. And incidentally, the variability should be expressed for film also.

This leads us to the measurement of roentgen exposures by dosimetry. The American National Standard PH 2.8-1975 also lists in the appendix calibrations offered by the National Bureau of Standards (NBS) to check dosimeters against the NBS standard. Certainly, our equipment manufacturers should be making more use of this service, if we are to move toward a precise radiographic technique. Pratt and Whitney (P & W) Aircraft Division of United Technology has addressed the film and chemical part of the X-ray system in their Standard on Testing Radiographic Film (MCL 017). They are in the process of evaluating how they could incorporate the American National Standard PH 2.8-1975 on film sensitometry into their specification in place of MCL 017. I urge other film users who are considering company specification on film to first review the ANSI document and see if you cannot use it in place of a company document. The proliferation of standards, not just in this area, but in all areas of NDT, must be stopped, if we are to sell management that standardization minimizes cost.

Records Maintenance

Proper processing and storage of radiographs has become an issue since the nuclear power field has come of age. Films must be kept for 40 years. Other high reliability systems are being engineered for longer life cycles and may require longer records retention. The ASTM Recommended Practice E 94-68 (1974) requires the user to follow manufacturer's recommendation in automatic processing and storage. Since this is unsatisfactory (consensus is not present), these sections are in the process of being rewritten. Some guidance may be obtained from American National Standard Specification for Photographic Film for Archival Records, Silver-Gelatin Type, on Polyester Base (1.41-1973). This standard is a new version of American National Standard Specification for Radiographic Film for Archival Records, Silver-Gelatin Type, on Cellulose Acetate Base (PH 1.28-1969). The new version is written for polyester base and also lowers the residual hypo level from 3 μg of thiosulfate per square centimetre (per side) to 2, for Class 2 X-ray films. The residual hypo level further reduces to 0.7 μg for fine grain films such as microfilm. It is obvious that low residual hypo levels are a must for archival retention of radiographs. Some specifications on this subject (P & W Requirements for Radiographic Procedure (XRM-1P)) have examined the method of determining residual hypo and concluded the silver densitometric method (presently in use) is three times the sensitivity of the turbidity method (used to set the level in American National Standard PH 1.41-1973). Depending on which route and level one chooses, I believe we should look at the maximum allowable, as follows:

Years Retention	Residual Thiosulfate, μg/in.^{2}
0	no limit
7	60 to 120
40	10 to 60

Work in this area will be accomplished by ASTM Committee E-7, Section E7.01.06 on Radiographic Methods. Anyone interested in working in the area should contact ASTM Headquarters.

Conclusion

Radiography is an extremely flexible NDT technique. Its flexibility is derived from the many variables which control test sensitivity and repeatability. Our challenge is to build on the present standards structure and to take NDT radiographic testing toward a precision technique.

APPENDIX

A List of Radiographic Standards

ANSI PH 1.41-1973, Specification for Photographic Film for Archival Records, Silver-Gelatin Type, on Polyester Base, American National Standards Institute.

ANSI PH 2.8-1975, Method for the Sensitometry of Industrial X-Ray Films for Energies up to Three Million Electron Volts, American National Standards Institute.

ANSI PH 4.8-1971, Methylene Blue Method for Measuring Thiosulfate and Silver Densitometric Method for Measuring Residual Chemicals in Films, Plates, and Paper, American National Standards Institute.

API 1104, Standard for Welding Pipe Lines and Related Facilities, American Petroleum Institute.

ANST TC 1A, Supplements A and G, Personnel Qualification, Recommended Practice, American Society for Nondestructive Testing.
ASTM E 94-68(1974), Standard Recommended Practice for Radiographic Testing, American Society for Testing and Materials.
ASTM E 142-72, Controlling Quality of Radiographic Testing, American Society for Testing and Materials.
MIL-STD-271E (Ships), Military Standard on Nondestructive Testing Requirements for Metals, U.S. Navy.
MIL-STD-453A, Military Standard on Inspection, Radiographic, U.S. Air Force.
MSFC-355B, Standard Radiographic Inspection of Electronic Parts, National Aeronautics and Space Administration.
P & W MCL 017, Testing Radiographic Film, Pratt and Whitney Aircraft Division of United Technology.
P & W XRM 1P, Requirements for Radiographic Procedure, Pratt and Whitney Aircraft Division of United Technology

ERRATA

STP 624 Nondestructive Testing Standards - A Review

Aman on Overview-Radiographic Nondestructive Testing Standards, pp. 63-73. Figures 2 and 3 should be reversed but the figure captions remain the same.

Arnold Greene[1]

Image Quality Indicators—Penetrameters

REFERENCE: Greene, Arnold, "**Image Quality Indicators—Penetrameters,**" *Nondestructive Testing Standards—A Review, ASTM STP 624,* Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 74–81.

ABSTRACT: The design of the present-day plaque-type penetrameter has changed very little over the past 35 years. Changes have been made in the size of the holes and the identification and correlation of material classes. Other users of penetrameters outside of the United States have been using a wire- or step-type design. Users of penetrameters as well as those who specify them have been under a cloud because of the variations from one code to another. A chart has been included to show the variations in the plaque style. Significant progress by ASTM Subcommittee E07.01 on Radiographic Practice and Penetrameters has been made to bring together the various code-making bodies toward accepting a unified design.

KEY WORDS: nondestructive tests, standards, penetrameters (radiation), image quality indicators, radiography, materials

History of the Penetrameters

Reviewing the past 36 years of image quality indicators (IQI), penetrameter design as it relates to sensitivity and definition of an industrial radiograph, one finds that there has not been a great deal of change.

In 1942, Russ[2] wrote, "The thorough and complete inspection of metals by x-ray examination required methods that are dependable." He goes on to say: "To determine whether these factors (methods) were properly controlled, suitable penetrameters (artificial flaws) should be placed on the specimen." The military recognized this need during World War II, and no less than three different designs were in use along with differing opinions as to the results that each was able to obtain. But in the overall view, the plaque-style hole equal to twice the plaque thickness was accepted in the United States and Canada as the primary design.

[1] President, Arnold Greene Testing Laboratories, Inc., Natick, Mass. 01760.
[2] Russ, G. A., "The Detectability of Penetrameters on X-Ray Radiography," *Industrial Radiography,* 1942, p. 29.

Ten years later, Miller and Tenney[3] published a paper, the importance of which is the fact that they had made a number of very important observations that remain valid today. The following is taken from this paper.

1. Penetrameter holes varied from 2-3-4 times the thickness ("T") to 1-3-4 T; 4-6-8 T; and minimum hole sizes of 1/32" and 1/16".
2. The use of a strip penetrameter (consisting of various steps of different thicknesses) with the same size hole, 3/16", in each step.
3. On the Continent, wire penetrameters were mainly in use.
4. They felt that theoretical considerations did not justify the diameter of a cylindrical hole being greater than the thickness of a penetrameter plate. Also, the penetrameter was not always placed in the best location.
5. They experimented with spherically shaped and wire penetrameters and concluded that the image of a wire was more easily visualized but that the conventional or plaque type was the best all around type. It merely required some understanding in use and caution in interpretation.

The American Society for Testing and Materials (ASTM) Subcommittee E07.01 on Radiographic Practice and Penetrameters has been active for many years in this area of penetrameter design and in the development of radiographic methods. The design of the ASTM IQI, penetrameter, resembles those of the American Society of Mechanical Engineers (ASME), American Welding Society (AWS), American Petroleum Institute (API), American National Standards Institute, (ANSI), U.S. Navy Military Standard on Nondestructive Testing Requirements for Metals (MIL-STD 271), Fabrication, Welding, and Inspection of HY80 Submarine Hulls (250-1500-1), Military Aircraft, Military Standard on Inspection, Radiographic (MIL-STD-453), Military Ordnance on Radiographic Inspection of Metals (MIL-R-11471).

Design Characteristics

Table 1 is based on information compiled since 1974. This table is a correlation of all of these designs.

Explanation of Table 1

Column II

A length of 1½ in. is the most common. MIL-STD-453 designates a length of 2 in. The extra length of ½ in. is used for indicating in lead figures the main chemical composition of the IQI.

Column III

API, AWS, and *ASME Boiler and Pressure Vessel Code,* (hereafter

[3]Miller, Norman and Tenney, Gerald, *Nondestructive Testing Magazine,* Fall. 1952, p. 28.

TABLE 1—*Current design characteristics of plaque-type penetrameter.*

I Military and/or Commercial Code Design Specification Reference Number	II Plaque Size	III Hole Dimensions[a] T = 0.005 to 0.050 in.	IV Thickness[b] T	V Tolerance	VI Material Category	VII Identification	VIII T = 0.050 in. to 0.160 inclusive	IX T = 160 in. up
A. ASTM Method E 142-72	½ in. × 1½	1, 2, 4 T	t/m 2%	± 10%[c]	5 classes of radio similar material	1. numbers based on thickness (T) of penetrameter in inches 2. notches 3. permanent marking	1 × 2¼ in. 1, 2, 4 T	4 T (round) 1, 2 T
ASME Section V	same	same	same	same	same	same	same	same
ASME Summer Section VIII 1973	same	same	same	same	same	same	same	same
A-1 MIL-STD-271D	same	same	t/m 2%	± 1/64-in. L/W ± 10% hole ± 1/64-in. hole Location	same	1. t/m normal material thickness in hundredths of inch 2. notches 3. permanent marking	same	same
250-1500-1	same	same	same	same (A)	3 classes (basically the same)	same	same	same
A-2 ASME Section III	same	1, 2, 4 T/0.250 slit (5, 7, 10)	t/m 2%	± 10%[c]	same (A)	1. same (A) 2. same (A) 3. same (A)	same	same

B. ASME VIII prior to 1973 Amendment	same	2, 3, 4 *T* minimum hole 0.062-in. slit 0.250 (5, 7, 10)	*t/m* 2%	*L/W* ± 1/64 in. thick and dia ± 10% hole location ± 10%	basic material	1. same (A) 2. no notches 3. marking (A)	same 2, 3, 4 *T*	2¼ × 1 in. plaque style 2, 3, 4 *T*
AWS	same	2, 3, 4 *T*	same	same	same (B)	1. same (A-1) 2. no notches 3. permanent marking	same (B)	same (B)
C. MIL-STD-453	½ × 2 in.	1, 2, 4 *T*	*t/m* 2%	± 10%[c]	basic material	1. *t/m* normal material thickness in hundredths of inch 2. no notches 3. lead figure for material design 4. permanent marking	size 2.85 in. × 1.0 1, 2, 4 *T*	size 4 *T* (round) 1, 2*T*
D. MIL-R-11471	½ × 1½ in.	1, 2, 4 *T*	*t/m* 2%	± 10%[c]	basic material except magnesium alloy	1. same (C) 2. same (C) 3. none 4. same (C)	2¼ × 1.0 in. 1, 2, 4 *T*	4 *T* (round) 1, 2 *T*
MIL-R-11471 magnesium alloy only Par. 4.1.2.2	same	same	*t/m* 3%	± 10%[c]	magnesium	same as (D)	2¼ × 1.0 in.	4 *T* (round) 1, 2 *T*

[a] Hole dimension in hundreds of an inch as a function of the plaque thickness (*T*).
[b] Thickness of the plaque—radiographic plaque thickness A, 0.005 to 0.050 in.; radiographic plaque thickness B, 0.050 to 0.160 in.
[c] Variation in all dimensions.

referred to as ASME Code) Section VIII, allows for holes that are 2, 3, 4 times the plaque thickness and a minimum hole size of 1/16 in. All others call out 1, 2, 3 *T* holes. ASME Code, Section III and Section VIII, prior to 1973 requires a slit 1/4 in. long and 0.010 in. wide in addition to the holes in the *T* range of under 0.010 in.

Column IV

The thickness of the IQI has been established to be 2 percent of the material being radiographed. This is sometimes referred to as *t/m* (thickness of material) or *d/mt* (design material thickness).

Column V

The quality control tolerance requirement of MIL-R 11471, ASTM, ASME (Sections III and V), and MIL-STD-453 call for a ± 10 percent variation in all dimensions; ASME, Section VIII, prior to 1973, calls for ± 10 percent hole and thickness measurements and a length and width requirements of 1/64 in.; 250-1500-1, MIL-STD-271 agrees with the latter ASME, Section VIII, and in addition, calls out a ± 1/64-in.-hole placement tolerance.

Column VI

The IQIs are complicated further by the need for material grouping. ASTM Subcommittee E07.01 has for the last ten years been involved with a task group to classify materials into groups of radiographically similar materials. Currently, ASTM Controlling Quality of Radiographic Testing (E 142-72), classified five groups. See Table 2, Material Groups and Penetrameter Grades. These same groups (groupings) are recognized by ASME and MIL-STD-271. Standard 250-1500-1 uses only 3 classes of material groups. They follow the ASTM Method E 142-72 listing. MIL-STD-453, ASME Section VIII, prior to 1973, AWS, API, and MIL-R-11471 call for the use of an IQI that is "the same material composition" of the material being radiographed.

Column VII

Identification falls into three basic headings as regards material identification.

1. Those that identify with a lead figure of the basic material that the IQI is fabricated (MIL-STD-453).
2. Those that identify with notches in the sides of the IQI and relate to

TABLE 2—*Penetrameter material—material grouping for penetrameter.*

Materials Group I, Penetrameters Grade I

All carbon, all low alloy steels, all stainless steels, and manganese nickel aluminum bronze (Superston). Penetrameters made of any of these materials may be used interchangeably for radiographing all materials in this group. In addition Group I penetrameters may be used when radiographing Group II, III, IV, or V materials but not vice-versa.

Materials Group II, Penetrameters Grade II

All aluminum bronzes and all nickel aluminum bronzes. Penetrameters made of any of these materials may be used interchangeably for radiographing all materials in this group or Grade I penetrameters may be used, provided quality level as applicable is maintained.

Materials Group III, Penetrameters Grade III

Nickel chromium iron alloy (Inconel).

Grades I or II penetrameters may be used provided quality level as applicable is maintained.

Materials Group IV, Penetrameters Grade IV

Nickel, copper, and all the nickel-copper or copper-nickel alloys. Penetrameters made of any of these materials may be used interchangeably for radiographing all materials in this group. Grades I, II, or III penetrameters may be used provided quality level as applicable is maintained.

Materials Group V, Penetrameters Grade V

Tin bronzes, gun metal, or valve bronze. Penetrameters made of these materials may be used interchangeably, or Grade I, II, III, or IV penetrameters may be used provided quality level as applicable is maintained.

Penetrameters of a lower grade number may be used for any materials group of a higher number, quality level as applicable to be maintained.

published material classes (Column VI) ASTM, ASME, MIL-STD-271, and 250-1500-1.

3. Those that do not identify with any marking that would be indicated on the processed film, ASME Section VIII prior to 1973, AWS, API, and MIL-R-11471.

Indication of the IQI *t/m* to be radiographed is divided into two categories.

1. Lead figures cemented to the blank end based on the actual thickness of the IQI (in hundreds of an inch).

2. Lead figures cemented to the blank end based on the normal material thickness of the material being radiographed (in inches), or the *T* of the IQI.

Column VIII

IQIs that are used with normal material thickness listed in the various codes, methods, and specifications as No. 60 to and through No. 160 or 2½ to and through 8 in., change the length and width dimension to accomodate the *T* holes. The only variation is with the MIL-STD-453. This is designed as 2.85 in. long. All others are 2.25 in. long. The width on all remains at 1.0 in. ASME Section VIII (prior 1973), API, and AWS continue to maintain the 2, 3, 4 *T* hole relationship.

Column IX

IQIs with normal radiographic material thickness listed in the various codes, methods, and specifications as over No. 160 or 8 in. use a circle shape with only two holes, 1 and 2 *T*. The circle dimension is four times the thickness (*T*) which again is based on 2 percent of the normal material thickness. MIL-STD-453 also uses this figure relationship.

Material Classes

Table 2 outlines the work of the late A. K. Hutton in developing a system to arrange a material classification. Fifty materials were listed by material designation, Hunter and Driffield curve density, mean atomic number, and physical density (grams per cubic centimetre and pounds per cubic inch).

The materials were subjected to a fixed radiographic technique in order to be categorized. This work is continuing in ASTM Subcommittee E07.01, and at this writing a tentative revision of ASTM Method E 142-72, Appendix A1, is being circulated to all ASTM Committee E-7 on Nondestructive Testing. This would allow the inclusion of titanium, aluminum, and magnesium in the grouping.

Mention was made earlier in this paper of wire penetrameters. These have been in use in Europe, Asia, and Japan. They are becoming more interesting in special cases such as radiography of honeycomb in the aircraft industry and contractors of welding fabrications, here in the United States, who are supplying fabrications to other countries, are being required to use these wire penetrameters. Other variations of wire penetrameters are used by the semiconductor industry. At this time, a standard on semiconductor wire penetrameters is in the ballot stage at ASTM.

M. J. Feaver, Central Electrical Research Laboratories (CERL), has proposed another development of the IQI. In a paper for the 1973 Seventh International Conference on Nondestructive Testing, Warsaw, Poland, he gave the following description:

> The design of the new IQI developed at CERL based on the above theory (Feaver, 1968, Carson and Feaver, 1973) consists of graded assemblies of plain steps for contrast measurement, and of wire or strip duplex elements of high density metal for unsharpness measurement.

General Conclusion

In reviewing the matter of IQI design, I find that the only work that needs to be done is a meeting of minds to (*a*) correct the fundamental plaque size ambiguities, (*b*) settle on one manner of indicating thickness being radiographed and quality control tolerance, and (*c*) classifying radiographically similar materials so they can be distinguished by a common system. Much of this work has been done by ASTM Subcommittee E07.01. The use of the wire IQI has overlapping values. With interest in this area rising, there should be a correlation forthcoming to close the gap in IQI design within the next two years.

E. H. Eisenhower[1]

Calibration of Radiation Sources for Radiography

REFERENCE: Eisenhower, E. H., "**Calibration of Radiation Sources for Radiography,**" *Nondestructive Testing Standards—A Review, ASTM STP 624*, Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 82–88.

ABSTRACT: A survey was conducted to find and evaluate published national standards for calibration of radiation sources used in industrial radiography. No standards were found on this specific subject, although several standards for medical radiography were discovered and summarized. The latter are inadequate for industrial radiography, but serve as general guidance on the subject. The need for an industrial standard was discussed, and a specific mechanism for developing such a standard was suggested if the need is considered to be sufficient.

KEY WORDS: nondestructive tests, standards, calibration, radiation, radiography, gamma rays, X-rays

Standards for the calibration of sources of ionizing radiation are of interest primarily for applications of X-rays and gamma rays. This paper will consider only these two types of radiation, with energies in the range from approximately several tens of kilovolts to several million electron volts.

Although the purpose of this paper is to discuss standards for *industrial* radiography, it will quickly become obvious that standards for medical radiography cannot be ignored. The primary reason why medical standards must be considered is the long history of activity in that area, resulting in a number of publications that may be generally applicable to industrial radiography.

For the purposes of this paper, source calibration means characterization of the radiation emitted by the source. The radiation characteristics of primary interest are energy and intensity. Those characteristics of secondary interest are beam uniformity (variations of intensity over the cross

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section of the beam) and beam stability (variations in source output as a function of time). Source calibration is achieved ideally by direct measurement of the radiation characteristics, using instruments designed for that purpose. Generally, it is not desirable to calibrate a source in terms of radiation properties determined indirectly by way of radiation effects. This method introduces a number of additional variables which are difficult to control. Thus a penetrameter is not useful for source calibration, but is instead (as defined in American Society for Testing and Materials (ASTM) standards) a device employed to obtain evidence on a radiograph that the technique used was satisfactory. Similarly, penetration curves supplied by the manufacturer (or exposure curves, or technique charts) are not ideal source calibrations because they are dependent upon the properties of the imaging system.

Existing Standards

One of the main purposes of this paper is an examination of existing standards for calibration of radiation sources used for industrial radiography and an evaluation of their adequacy. Therefore, a search was conducted for standards specifically concerned with calibration of X- and gamma-radiation sources. A number of catalogs were examined which are published by standards-producing organizations which might be involved in this area. The survey included a visit to the National Bureau of Standards' (NBS) reference collection of engineering and related standards which includes over 200 000 standards, specifications, test methods, codes, and recommended practices issued by U.S. technical societies, professional organizations, and trade associations. Relevant military specifications also were examined. Although it is possible that the standard being searched for was overlooked, it appears safe to conclude that a standard concerned specifically with calibration of X- and gamma-radiation sources used for industrial radiography does not exist at the national level.

Since no specific standard was found, it is impossible to do an evaluation of adequacy. There are, however, a number of published standards relating to calibration of radiation sources used in medical applications. Since these standards were prepared for a different purpose, they would be of limited value for industrial radiography. However, some parts of these standards could serve as general guidance or as the basis for development of an industrial standard. Thus it is worth examining them in a general manner.

NEMA XR3-1970

Perhaps the most useful existing standard is by the National Electrical

Manufacturers Association, entitled Test Methods for X-Ray Equipment (NEMA XR3-1970). As stated in the scope, "This publication defines test methods used to measure the significant characteristics of equipment used in diagnostic medical X-ray systems. The test procedures are established so that a complete system of functional elements of the system may be tested." Part 2 specifies those tests by which performance characteristics of X-ray machines shall be determined. Part 2.02 specifies radiation tests to be made after the X-ray machine has been calibrated and tested as specified for peak kilovolt and milliampere meter readings, milliampere stability, temperature stability, and timer accuracy.

The radiation output tests consist of output linearity and repeatability (accuracy of duplication). Output linearity is tested over a wide range of peak kilovolts and milliamperes. The radiation output is measured using an ionization chamber X-ray radiation measuring device. A series of measurements of milliroentgen/milliampere-seconds versus milliamperes (mR/mAs versus mA) is taken for rated output voltage, and for 80, 60, and 40 percent of rated output voltage. The plotted values of each series shall not vary by more than the following specified value.

$$\frac{\text{mR/mAs max} - \text{mR/mAs min}}{1/2\,(\text{mR/mAs max} + \text{mR/mAs min})} \leqslant 25\%$$

The repeatability test is conducted to determine the accuracy of duplication of the equipment by noting the difference in milliroentgens for a series of exposures made without changing the settings of the X-ray machine. The values for the maximum percent variation in milliroentgens for a series of ten exposures shall not vary by more than

$$\frac{\text{mR max} - \text{mR min}}{1/2\,(\text{mR max} + \text{mR min})} \leqslant 8\%$$

American National Standard N449-1974

The next standard to be considered is the American National Standard Guidelines for Maintaining Cobalt-60 and Cesium-137 Teletherapy Equipment (N449-1974). Part 4.1.5 is concerned with spot-check and full calibration measurements. It states the following.

> The radiation output of the machine, whether measured in air or in a phantom, shall be reproducible within ±3% when taking into account calibration of the source and radioactive decay. A shift in output during the useful life of the source may be due to unidentified radioactive contamination of the source, a shift in pelletized or powdered material encapsulated within the source, or a malfunction of the source shutter mechanism. Spot-check mea-

surements are used as constancy checks to verify the calibrated output of the machine. In the case of new cobalt-60 sources, spot-checks are made to confirm the predicted rate of radioactive decay as well as to check on machine performance. The spot-check is a determination of the exposure rate, dose rate, or a quantity related in a known manner to these entities for one typical set of machine operating conditions. Full calibration is the determination of exposure rate or dose rate and all related quantities (such as field-size dependence, backscatter factor, inverse-square correction, and effect of trimmer position).

The reader is then referred to five other documents which deal specifically with calibration of teletherapy machines.

NCRP Report 33

Report Number 33, Medical X-Ray and Gamma-Ray Protection for Energies up to 10 MeV—Equipment Design and Use, of the National Council on Radiation Protection and Measurements (NCRP) is concerned with medical X-ray and gamma-ray protection for energies up to 10 MeV. (This publication superseded, in part, NBS Handbook 76 (NCRP 26) on medical X-ray protection up to 3 MV). Part 5, on therapy equipment calibration guides, includes the following:

5.2 CALIBRATION

A calibration of the therapy apparatus *shall* be performed by or under the direct supervision of a qualified expert before the apparatus is first used for medical purposes. The calibration *should* include at least the following determinations:
5.2.1 The exposure rate or dose rate for the range in field sizes used and for each radiation quality and for each treatment distance used for radiation therapy.
5.2.2 The radiation quality (e.g. half-value layer when appropriate or effective energy) for every combination of kVp and filter used for radiation therapy.
5.2.4 The uniformity of the radiation field and its dependence upon the direction of the useful beam.

5.3 RECALIBRATION

The user *should* make or *should* have made appropriate determinations as described in 5.2 in the following circumstances:
5.3.1 Whenever the beam monitor or other meter related to exposure rate or dose rate shows a continued, significant change in its normal reading.
5.3.2 Following major mechanical or electrical alterations of the radiation source, its housing, power supply or controls, or following replacement of the radiation source, or following reinstallation of the apparatus in a new location.

5.3.3 At least once in every calendar year except that recalibrations are not required so long as spot checks, as defined below, indicate no significant change in the exposure rate or dose rate.

5.4 SPOT CHECK MEASUREMENT

A spot check measurement consists of determining the exposure rate or dose rate or a quantity related in a known manner to these entities for one typical set of operating conditions. Spot checks *should* be made periodically (for X-ray therapy equipment, at least once a month or after every 50 operating hours, whichever is the longer time interval). A log *shall* be kept of all spot check measurements.

BSI 3513-1962

The last specific standard to be considered is the British Standards Institution Specification for Gamma-Radiography Sealed Sources (BSI 3513-1962). It applies to a range of sealed gamma-ray sources for use in radiography and covers sources of activity up to approximately 100 Ci of cobalt-60 or 300 Ci of cesium-137 or iridium-192. This specification says very little about source calibration. In Part 3 it states, "The radiation output from a radiography sealed source is the exposure dose rate, expressed in roentgens per hour in air 1 metre from the source in line with the major axis of the source, as far as possible in conditions of freedom from scattered radiation." Part 5 states, "Sources shall be produced according to a list of nominal activities published by the supplier. The supplier shall specify a nominal radiation output for each nominal activity and individual sources shall have an activity and radiation output within ±20 percent of these nominal values." The remainder of this specification is concerned with source construction and integrity.

Need for a Standard

The specific standards mentioned here are not directly applicable to industrial radiography, but they could provide guidance for development of an industrial standard.

Since there are no comparable standards for industrial radiography, even though it has been practiced for the past 40 to 50 years, one naturally wonders about the need for such standards. Presumably standards for calibration of industrial radiography sources would have been developed by now if the need for them had been great enough. Perhaps in-house standards, which do not have national distribution and recognition, have been developed and are adequate for local needs. Perhaps there is no need for such standards at the national level, and the effort required to produce them would not be cost effective.

Recent discussions with a limited number of users and producers of industrial radiography equipment have revealed some interest in source calibration standards. Apparently the art of radiography now has reached that level of sophistication where it could use such standards to its advantage. There is, however, no obvious national consensus in favor of development of source calibration standards at this time.

There are a number of reasons for developing a standard in general. These include quality control, safety, interchangeability, adaptability, performance, testing, classification, reliability, procurement, and training. A number of these reasons are applicable in consideration of the need for source calibration standards.

Perhaps one of the more obvious needs is for procurement purposes. If an adequate standard were available, it could be of considerable value in procurement specifications. A good standard also would include methods of testing to determine whether specifications have been met. When the manufacturer, dealer, installer, and purchaser all have a common standard they can refer to regarding performance specifications and test methods, the procurement process is facilitated considerably and real economic benefits can be realized.

From an operational standpoint, economic benefits can result from a satisfactory source calibration. Adequate knowledge of the radiation characteristics for a particular machine should result in less retakes and thereby enable savings of the labor and materials costs expended in unsatisfactory radiographs. Improved efficiency of work scheduling also should be possible through the use of an adequate source calibration standard. Planning also could be done more effectively, particularly in those cases where long exposures will occupy space which is needed for other uses.

An obvious operational advantage could result from the use of an adequate standard for source calibration in those cases where many operators are used to operate many machines. If the machine is well calibrated, an operator should be able to produce acceptable radiographs in a relatively short time from an unfamiliar machine. This should save a considerable amount of trial and error, and the costs associated with such an unproductive method. It also would allow more efficient use of a given number of operators and machines.

A national standard for source calibration also would make duplication and comparison of results more meaningful than at present. If both laboratories have calibrated their sources by the same specified method, the level of confidence with which comparisons can be made should be increased.

A somewhat less obvious advantage would be increased safety for the operator and the public. If the source characteristics are well known, particularly in an open installation where ropes or barriers must be employed, safety measures can be taken with increased confidence and with less absolute reliance on a survey meter.

For isotopic sources in particular, a reliable, standard method for calibrating source output would enable the user to determine whether the source strength delivered is the same as that ordered and would enable him to maintain a record of disintegration rate which also might give an indication of source impurities.

Possible Future Project

The decision on whether or not to begin development of a source calibration standard must be made primarily by the users and producers of industrial radiographic equipment. The content of such a standard would be determined by these same interested parties. Decisions regarding required accuracy of measurements would have to be made, and those accuracy requirements would strongly influence the type of measurement procedures and instruments to be specified. At the extremes of the energy measurement range, problems such as energy dependence and electronic equilibrium are encountered and must be handled appropriately.

If it were decided to begin a project which would lead to a national standard for source calibration, a suitable working group or subcommittee should be formed under the auspices of an appropriate national organization. An example would be the American National Standards Committee N43 on Equipment for Non-Medical Radiation Applications. The scope of this particular committee is as follows: "Standards pertaining to products and equipment for non-medical scientific, industrial, and educational uses, involving ionizing radiation sources including radioactive materials, accelerators, and X-ray equipment but excluding nuclear reactors."

Industrial radiographic equipment fits very well within this scope. Four subcommittees concerned specifically with the design and use of X- and gamma radiography equipment exist in American National Standards Committee N43, some of which are just getting started in their activities. However, none of these subcommittees plans to concern itself specifically with standards for calibration of radiation sources. If it were decided that an American National Standard is needed in this area, and a writing group were formed for that purpose, that activity could be included in the American National Standards N43 program.

W. J. McKee[1]

Standards for Real-Time Systems Used with Penetrating Radiation

REFERENCE: McKee, W. J., "**Standards for Real-Time Systems used with Penetrating Radiation,**" *Nondestructive Testing Standards—A Review, ASTM STP 624,* Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 89–101.

ABSTRACT: In the area of radiography, there has been a substantial effort to find a reasonable approach in formulating standards to aid us in determining the level of performance that can be expected from a certain group of equipment and then determine desired or recommended procedures that would provide the optimum results obtainable with the equipment described.

We now approach the area of real-time systems, those of electronic imaging and gaging, for similar purposes. In many ways, there are close correlations to the classic film techniques of radiography but there are also many areas that are unique to these electronic systems, and we must deal with them now.

KEY WORDS: nondestructive testing, standards, data storage, measurement, real-time systems, signal manipulation, conversion screen, statistical integration

What do we mean by electronic or real-time systems? In the area of radiography, we are all familiar with the end result being a film with variations of gray from black to white. We have a base plus fog as the minimum density, and the maximum density is determined by the amount of exposure, the film used, and the processing involved.

The area of gaging is similar to this in that the equivalent information can be seen in the form of an electronic signal which varies as the detected radiation varies,[2] due to the absorption, scatter, or excursion of the source radiation incident upon the object (Fig. 1). In gaging,[3] the typical approach is that of a differential measurement between the raw beam of radiation and the detected radiation after passing through the object. We

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[2] *Practical Applications of Neutron Radiography and Gaging, ASTM STP 586,* American Society for Testing and Materials, 1976.

[3] *Nondestructive Testing Handbook,* American Society for Nondestructive Testing, Ronald Press, New York, 1963.

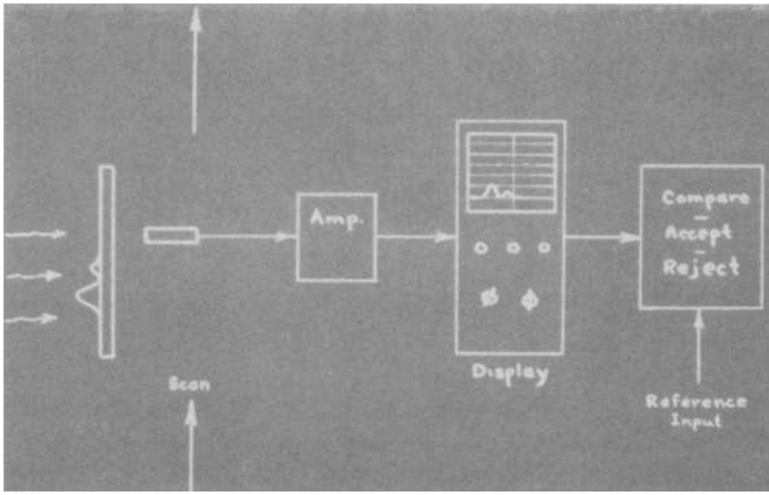

FIG. 1—*Basic gaging approach.*

see here a useful tool for a production line (Fig. 2) where a go-no-go criteria can be met by the simple deflection of a metering device of a level detected between certain predetermined limits of acceptance. In essence, we are looking at a simple signal corresponding to the shades of gray of the radiograph. A similar signal could be produced using a microdensitometer to scan the surface of the radiograph of the object.

In the real-time imaging system, we can have a video image that is very close to being identical with the radiograph. The basic differences are as follows.

1. We have an inhomogeneity of surface structure due to the scanning techniques used.[4] This is particularly true if there is a digitizing of the

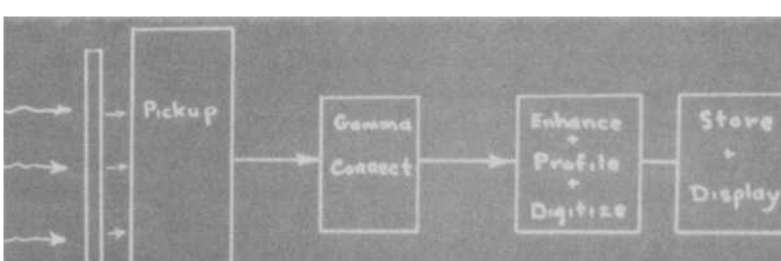

FIG. 2—*Manipulation and decision.*

[4] *Research Techniques in Nondestructive Testing,* Academic Press, New York, 1970.

analog data and subsequent reconstruction of the image onto a television monitor.[5]

2. We are able to demonstrate data as the object is in motion. The limitation of viewing only static data is no longer a factor in many applications (see footnote 4).

3. We have the capability of manipulating the data and producting surrealistic impressions (Fig. 3) of it as well as show flaws that may have been obscure (Figs. 4 and 5) even to the trained observer.

4. We can correct for a gamma curve that is not optimum, change the maximum density viewed, or then assign colors[6] to shades of gray (Figs. 6 and 7) to assist in determining those portions of the object that are of identical cross sections with respect to the input radiation (Fig. 8).

There are a vast number of methods to record as well as manipulate the data involved here (Table 1). There is a possibility of using statistical integration which will give a more pleasant image to the eye as well as provide the necessary information to be displayed that may not have been present without such integration.[7] We must use a different recording medium than radiographic film. We will use photography, video tape, electronic memories, and paper (see footnote 4).

You can see the differences as well as similarities to the classic film techniques. We are going to enter the world of the computer, television, photography, conversion devices, and many more that have begun to make ripples on the water. We have a tremendous challenge ahead and we must meet it now!

When we think of standards for radiography, we think of the type of film that will give us a certain resolution, density, speed, and gray scale,

TABLE 1—*Recording and signal manipulation methods.*

Recording methods
1. video tape recorder
2. video disk recorder
3. paper
4. film, 35 mm or Polaroid
5. film, kinescope recorder
Signal manipulation methods
1. analog-to-digital conversion
2. color profiling
3. edge enhancement
4. gamma correction
5. statistical integration
6. electronic substraction

[5] *Cardiovascular Imaging and Image Processing,* National Aeronautics and Space Administration/Society of Photo-Optical Instrumentation Engineers, 1975.

[6] Clifford, Joe, International Imaging System, Inc., private communication.

[7] Rundquist, Dave, Science Applications Inc., private communication.

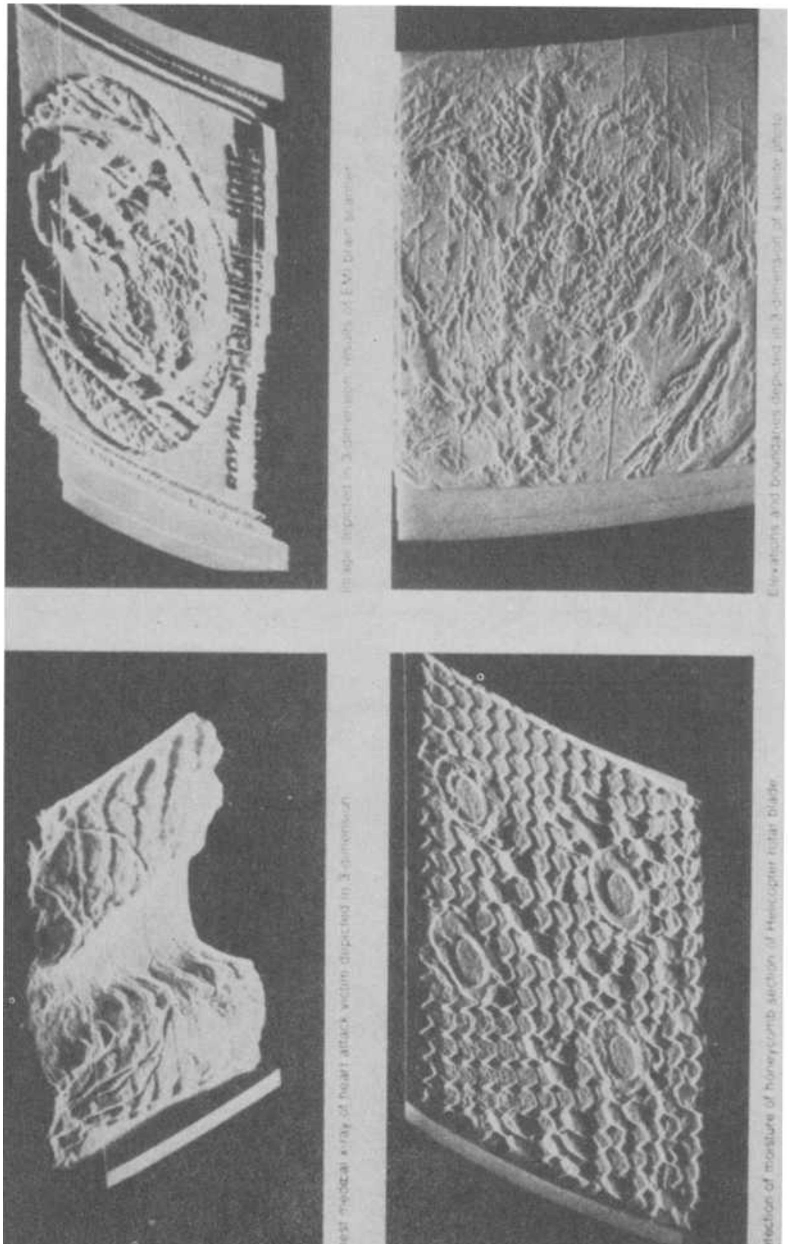

FIG. 3—*Enhancement and display.*

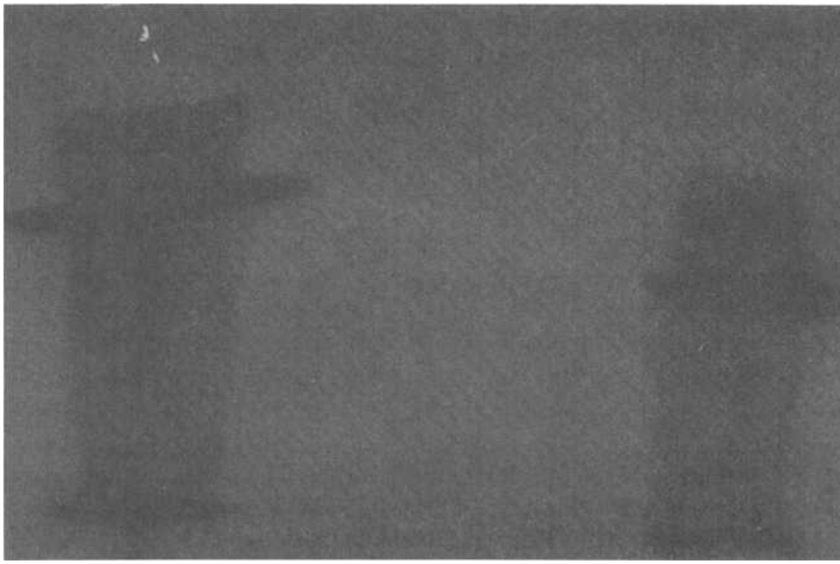

FIG. 4—*Turbine blades, radiograph.*

FIG. 5—*Turbine blades, enhanced.*

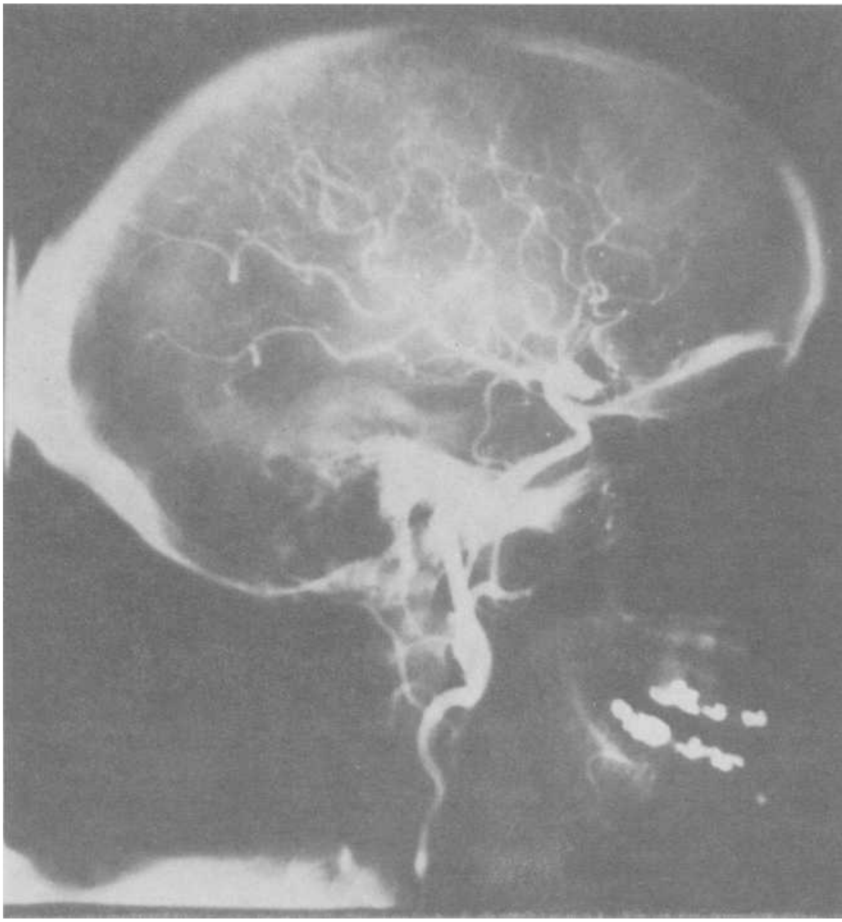

FIG. 6—*Skull, radiograph.*

for example, something that can be exposed and developed with certain chemistry viewed on a certain apparatus filed in a specified way for archival records. We are concerned with scattered radiation, in some cases with secondary radiation, and with some techniques we must consider many different types of radiation in the same beam.

All of these factors must be considered and every possible correlation made for the effort ahead to be an approach with knowledge of past success or failure in the many varied approaches that have been taken by professionals in the area of classic "film radiography." We have been involved and we can learn by monitoring the mistakes and finding a new approach to areas that have proven troublesome in the past.

There is only one logical approach to this staggering problem; we must

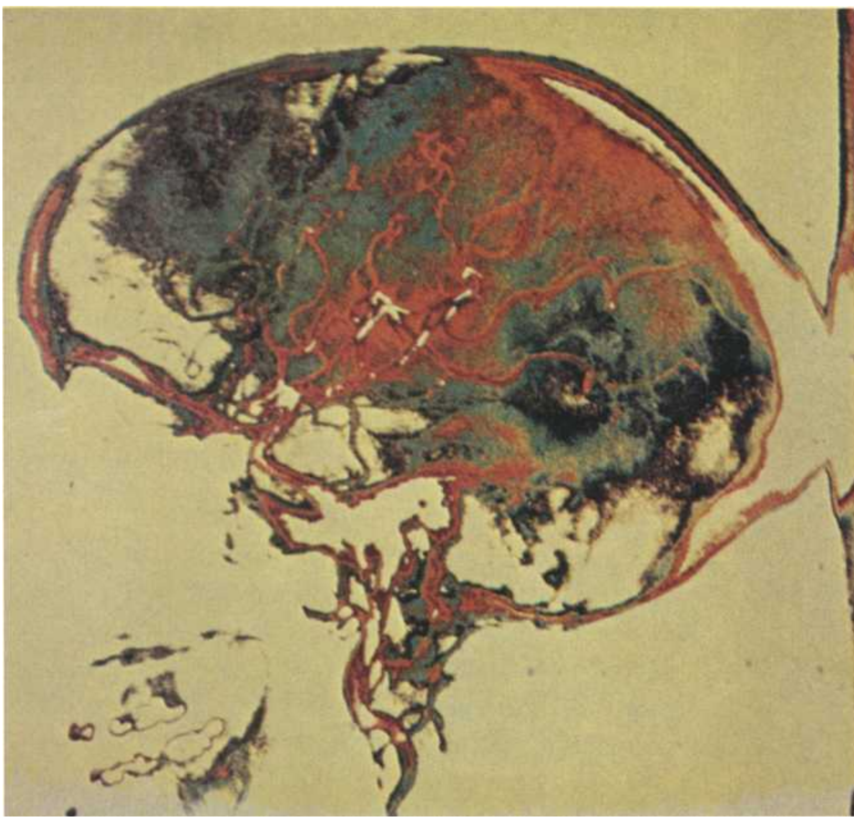

FIG. 7—*Skull, color enhanced.*

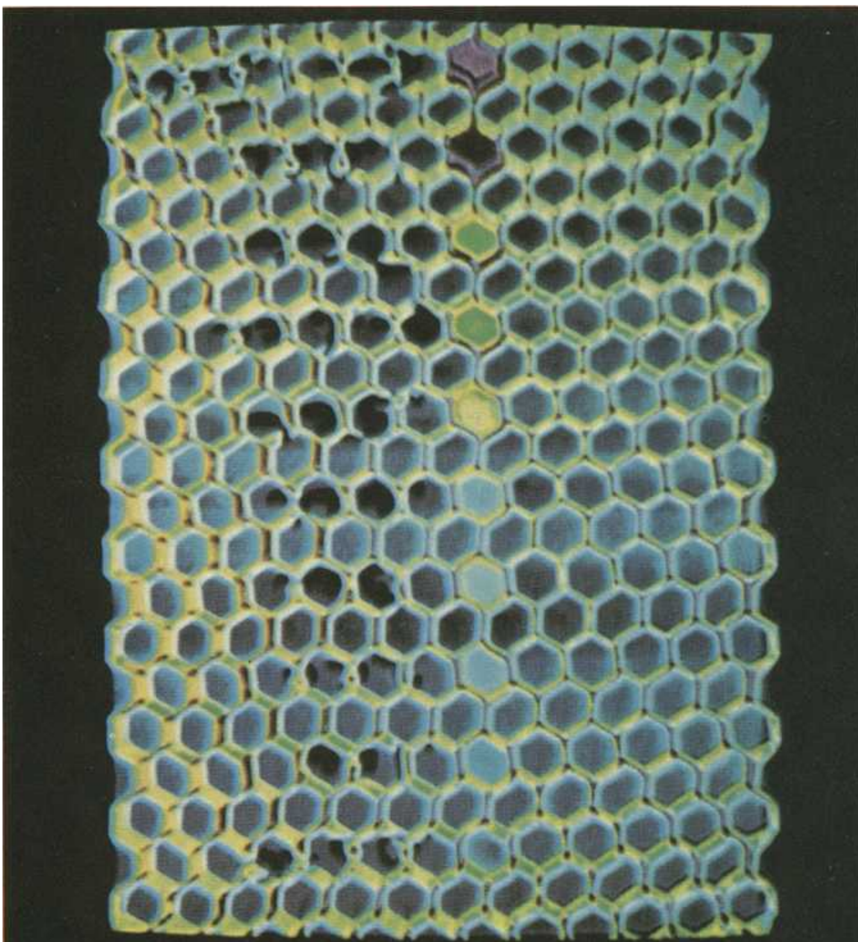

FIG. 8—*Limited densities assigned colors.*

decide what we would like to be able to refer to in the future in order to communicate our needs to someone that is to do a job for us.

1. We want a certain resolution.
2. We want to see every flaw visible at a certain contrast level.
3. We would like hard copy of the test results.
4. Can signal manipulation be relied upon to give us more information than a trained interpreter?
5. What equipment will do our job? How do we use it?
6. Is there a recommended practice for this type of equipment?

How do we approach the problem of standards for electronic systems?

Let me discuss with you the approach taken by ASTM Committee E-7 on Nondestructive Testing (Table 2). About a year and a half ago there was a small group of interested people who formed into an *ad hoc* committee under the guidance of ASTM Subcommittee E7.01 on Radiographic Practice and Penetrameters. Their task was to consider the working areas of the group, yet to be formed officially, generate a proposed scope for the group, and report their recommendations to ASTM Subcommittee E7.01, when ready.

The proposed scope that subsequently was submitted listed the following as some of the possible working areas for the larger group to focus their attention on:

1. Recording methods for the data
2. Recommended practices
3. Image quality indicators specifically for real time imaging
4. Parcel and baggage screening systems
5. Automated interpretation equipments
6. Classification of various electronic systems and peripheral equipments

There were others, but this will give you an indication of the overall com-

TABLE 2—*Proposed scope for future work.* [a]

To develop recommended practices, image quality indicators, and a quality standard reference system for inspecting materials for use with non-film, real-time image detection systems used with penetrating radiation sources. Specifically, but not necessarily exclusively, these sources are X-ray, gamma ray, and neutron sources.

Possible working areas are as follows:

1. Recording media for real-time imaging systems
2. Recommended practices for real-time imaging systems
3. Image quality indicators for real-time imaging systems
4. Quality references and interpretation guides for real-time imaging systems
5. Classification of electronic imaging systems
6. Automated interpretation of electronic imaging systems
7. Non-film security surveillance systems

[a] Possible approach by ASTM Committee E-7 as recommended by the *ad hoc* committee under direction of ASTM Subcommittee E07.01.

plexity of the problem at hand. We have a mind boggling job ahead. Where do we start?

That is probably the easiest question to answer. We look at the work that has been done in radiography to date and apply that portion that is applicable. We then attempt to define the areas that concern us the most and proceed with reaching the goals we set.

Did We Set Goals?

There are a couple of approaches we could consider here; we could take the job on, one step at a time and see what happens, or we can try to determine where we want to be and find a way to get there from here. I think we *can* get there from here!

The people that have worked in film radiography and standards for it have spent much time and have put forth a substantial effort in trying to identify work areas and, in many cases, indicated some of the pitfalls that will require further efforts, as they apply to electronic as well as film techniques.

It would be foolish for us to disregard these efforts and only good business to learn from their mistakes.

In the area of film radiography, we see an approach that may not be correct for electronic detection. In film work it is common to divide the overall technique into its basic areas and treat them separately. Could it be that with the real-time systems' approach we might try to use the Black Box analogy (Fig. 9) and not look at the individual equipment involved in producing the end result but simply define an end result and then categorize the equipments so as to give the interested parties a "feel" for the capabilities of the overall system and then of the components that make

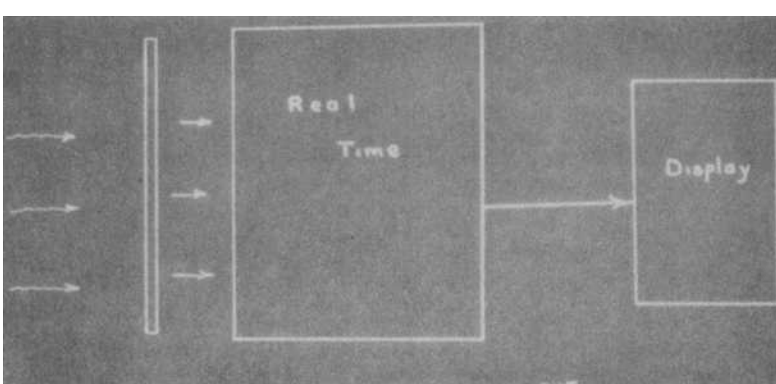

FIG. 9—*Black Box approach.*

it up? Shall we limit our approach to the equipment that produce a signal with a radiation input and not to the signal manipulation devices? If we do that, we must concede to doing less than would be beneficial to our constituents. With electronic systems we usually can "see" more (Figs. 10 to 13) with some type of peripheral device to aid us other than simply converting the input radiation into a visible representation. Then where do we draw the limit? Do we draw a limit? Possibly we can address ourselves to the basic equipments that extract the information from the beam and add other devices as the work load allows or as the consensus dictates.

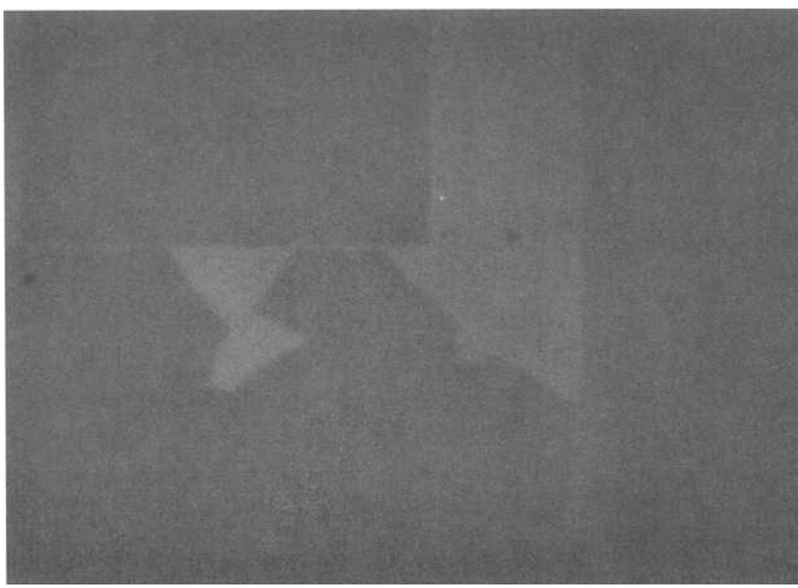

FIG. 10—*Obscure cracks, radiograph.*

Conclusion

There is a tremendous job ahead of us and we now must concede the fact that there will be electronic or real-time detection devices in the future of nondestructive testing. We must act to engage ourselves in the effort of formulating the standards for use with them. If we look ahead, we will find a reasonable approach and our job will be easier. Where do we want to be in three years? Two years?

I know there are those of us who will not have a direct interest in real-time techniques but we need you to assist us in our attempt.

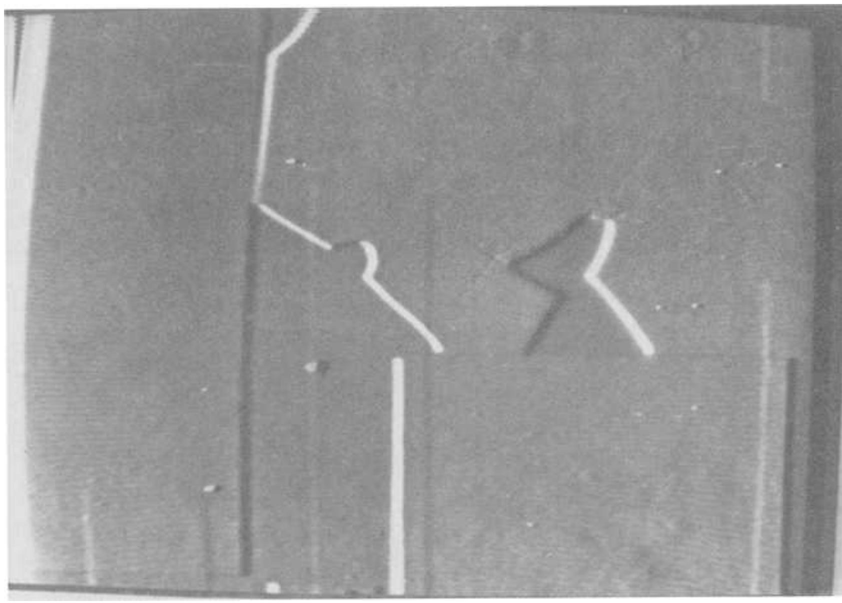

FIG. 11—*Enhancement of details.*

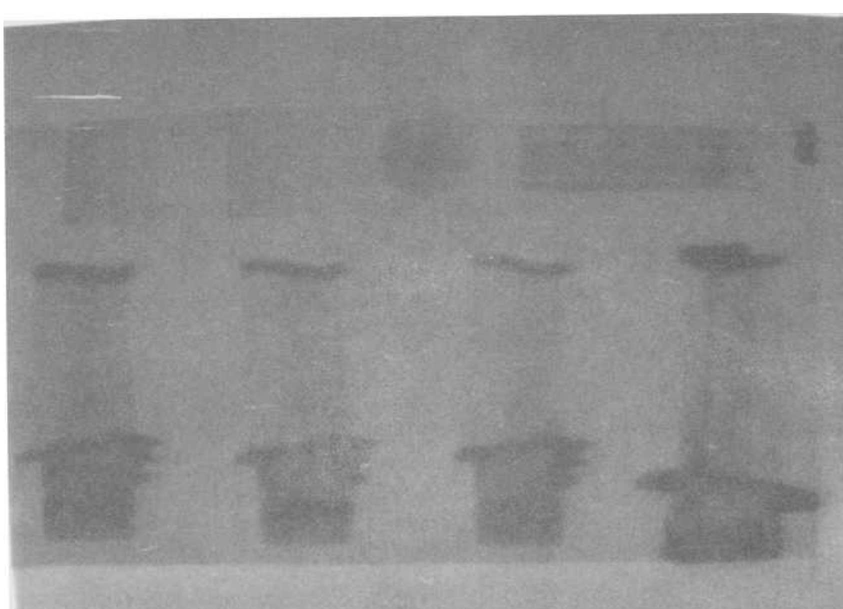

FIG. 12—*Unenhanced radiograph.*

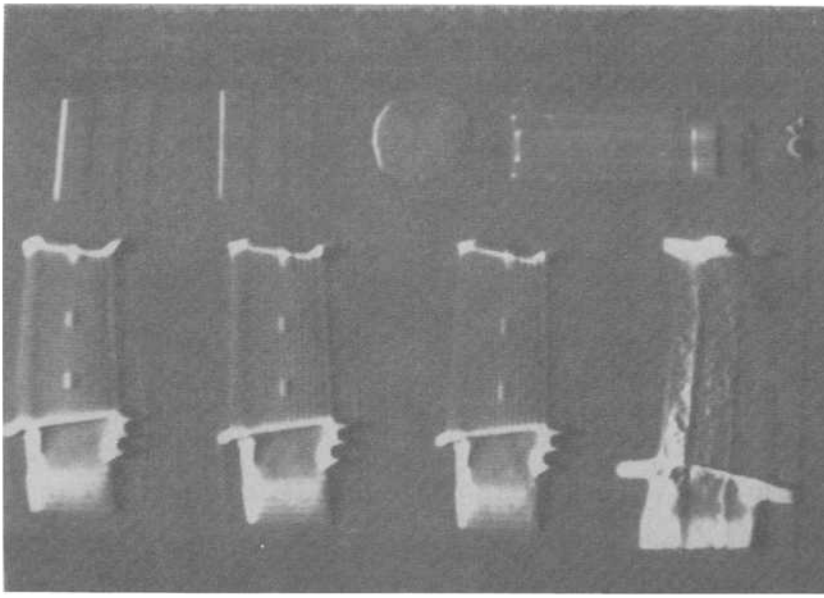

FIG. 13—*Utilizing enhancement.*

Acknowledgments

I would like to express my appreciation to the members of ASTM Committee E-7 who had the foresight to begin this effort and those who help to accomplish it, and the International Imaging Systems for their assistance.

Daniel Polansky[1]

Classification of Industrial X-Ray Film

REFERENCE: Polansky, Daniel, "**Classification of Industrial X-Ray Film,**" *Nondestructive Testing Standards—A Review, ASTM STP 624,* Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 102–107.

ABSTRACT: A review of the efforts of a task group of American Society for Testing and Materials (ASTM) Committee E-7 on Nondestructive Testing to classify industrial X-ray film will be presented. The introduction of new film and especially automatic X-ray film processors with their relatively high temperature chemistry have changed considerably the sensitometric curves of film relative to that produced at normal temperature with hand processing. The objective of the task group is to classify film in order to indicate potential film performance and differentiate between the films.

The several methods of classification based on speed, speed and gradient, and mass of silver on a film will be discussed. The difficulties of specifying a system that may be too narrow or too broad will be discussed. The equating of film characteristics to the subjectively determined evaluation of radiographic film quality has not been accomplished satisfactorily. Systematic exposures of a standardized test plate have been made at several facilities and will be interpreted by several observers. The analysis of these data may help in equating film characteristics to radiographic film quality and, therefore, be the basis for a film classification system.

KEY WORDS: nondestructive testing, standards, radiography

This paper is a review of the efforts of a task group of American Society for Testing (ASTM) Committee E-7 on Nondestructive Testing to develop a system of classifying industrial X-ray film.

Early in the 1960s, the manufacturers introduced new and additional film into the market. The advent of automatic processors with their higher processing temperatures and shorter time cycles affected the speed and apparent graininess of film. These factors coupled with the desire by film users to have a system of comparing the quality of competitive film led to the establishment of the film classification task group.

A review of the literature indicated that the Federal Specification on Film, Radiographic, Industrial (L-F-350, 24 Aug. 1959) and the ASTM

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Committee E-7 classification were inadequate. Table 1 indicates the severe limitations of the present system.

What had been acceptable in the days of hand processing of film and a rather limited film selection was leading to a distortion of the concept of film classification. The introduction and rapid acceptance of automatic processors resulted in detectable radiographic quality differences, that is, if a given type of film is processed by hand and by automatic processing, the films, when compared by a radiographic interpreter, have a detectable difference in what is stated loosely as image quality. The result of this was that a given film could be in several classes, and conversely, several classes of film could be said to be of the same class dependent upon the processing. The result was that most film were now rather remarkably Type 1, Class 1 according to Federal Specification L-F-350. The objective of the task group in ASTM was to develop a classification system that would (*a*) differentiate between the films of a given company and (*b*) give a relative indication of film performance in a radiographic system.

Speed-Gradient Method

The initial attempt on classification was to base it on speed and gradient. The manufacturers stated that the speed of a given film could be maintained within $\pm$ 10 percent. The determination of speed and gradients at selected densities and using definite X-ray energies hopefully would result in tabular data similar in form to a previous classification system that would separate the films (Federal Specification L-F-350). The mass of data developed at the five X-ray energies with the many films and differing chemistries could not be reduced to a form which the committee could agree would classify the films.

Contrast/Speed Index

In 1967, the committee took under consideration a method proposed

TABLE 1—*Types of industrial radiographic film*[a]

	Description		
Film Type	Speed	Contrast	Graininess
1	low	very high	very low
2	medium	high	low
3	high	medium	high
4	very high	very high	

[a]ASTM Recommended Practice for Radiographic Testing (E 94-68(1974)).

by this author and Criscuolo.[2] Film would be classified according to a number achieved by multiplying the average gradient between two arbitrary densities and the reciprocal of the square root of the speed to achieve a central density $\eta = \bar{G}\sqrt{r}$. The concept here was that the higher the average gradient, the better the contrast sensitivity, and, secondly, the longer the exposure required, the better the signal to noise ratio. The product of the two would indicate that film with the largest number would have the optimum potential in a radiographic system. The first index was taken of the average gradient between densities of 0.50 and 2.50 and the exposure, at a density of 1.50. To eliminate the objection that unique films might be created whose sensitometric curve might be optimized for this density range, an additional index, η_2, was calculated between densities of 2.00 and 4.00 and the exposure measured at 3.00. Table 2 indicates how this index discriminates between film exposed to 10-MeV radiation. This approach did differentiate between the films of a given company, showed an effect produced by different chemistries, and indicated a difference between hand development and automatic processors. Some of the objections to this approach were that the index did not have a direct bearing on radiographic sensitivity, and changes in chemistry could effect film grain and fog level with no change in the contrast speed index. A strong objection to the system was that it did not give a constant value, that is, when the experiment was repeated months later the absolute value of η varied for a given film. Small errors in locating points in the characteristic curve gave relatively large errors in calculating the average gradient.

Speed-Multiple Gradient

An approach on film classification as proposed by Aman was based on using a speed change of 30 percent to separate the films and at a given speed to have gradient classes within the density range chosen. The authors chose the speed as measured to reach a density of 2.50 as one reference and used the density range of 1.50 to 4.00 to establish gradient classes. As Table 3 shows, at a given speed rating, the average gradient measured between the range chosen determines its class. A film which has a speed between 0.832 and 1.10 is speed rated 52 and which has an average gradient between 13 and 16 is gradient classified as N; the film classification therefore would be 52N. As Aman stated, the determination of the width of the speed and gradient classification would be difficult. The committee accepted the 30 percent speed difference but could not agree on a gradient

[2] Polansky, D. and Criscuolo, E. L., "A Method for the Classification of Industrial X-Ray Film," *Proceedings*, Fifth International Conference on Nondestructive Testing, Montreal, Canada, 1967.

TABLE 2—*Contrast/speed index.*

		$\eta_1 = \gamma_1 \sqrt{r_{1.5}}$ Automatic Processor		Hand Development	$\eta_2 = \gamma_2 \sqrt{r_{3.0}}$ Automatic Processor		Hand Development
Class	Film	Chemical A	Chemical B	Chemical C	Chemical A	Chemical B	Chemical C
	1	4.7	3.8	5.6	13.2	11.0	19.2
	2	3.9	5.8	7.5	13.9	20.0	32.6
1	3	2.0	1.6	2.6	6.4	5.0	7.9
1	4	2.4	1.9	2.4	7.0	6.8	13.3
1	5	3.1	3.8	3.8	10.5	8.8	13.8
2	6	1.1	1.0	1.1	2.6	3.0	3.1
2	7	1.1	1.8	1.4	3.7	3.0	4.9
2	8	1.2	0.92	1.6	3.6	3.5	5.3

TABLE 3—*Classification of industrial radiography systems.*

Speed (D = 2.5)		Gradient Class (Density 1.5 to 4)				
Number	$1/R$	L	M	N	O	P
48	0.489 to 0.644	...	...	...	...	...
50	0.645 to 0.832	...	...	...	...	...
52	0.833 to 1.10	7 and 8	9 to 12	13 to 16	17 to 20	21 to 26
54	1.11 to 1.43	...	...	...	...	...
56	1.44 to 1.89	...	...	...	...	...

classification. The probability of having film uniquely specified in a system without competition was not acceptable for a general system.

Speed System

During the next several years, attempts were made to classify films by defining the response in a radiographic system. Details such as X-ray energy, use of lead screens, type of processing, and use of manufacturers recommended chemistry were delineated and data gathered. These data essentially gave the speed at an arbitrary density. The concept of speed alone was not acceptable to many members of the committee.

Exposure-Mass of Silver System

A new approach was presented by Splettstosser which stated that the film index should be proportional to the square root of the effective exposure, $\eta = (RAg)^{1/2}$. At the recommended energy of 200 kV, the product of the exposure in roentgens and the quantity of silver per unit area is proportional to the effectively utilized exposure in the emulsion. As the mass of silver is decreased in the emulsion, the exposure required to achieve a given density increases rapidly due to the inefficiency associated with multiple exposure to grains. This system tends to overrate slow speed films. For this reason and the fact that for a given mass of silver it is possible by sensitization methods to speed up development at a given exposure, the method was not adopted.

Relative Graininess System

The committee then reviewed a proposal for film classification presented to the International Institute of Welding in 1970 by Schnitger and Mundry.[3] This paper, as one of its approaches, recommended a relative graininess system. All films to be evaluated are developed in a standard

[3] Schnitger, D. and Mundry, E., "Classification of X-Ray Film," private communication, DIN 54-111, Nov. 1970.

system. The negative of the finest grain film is projected as a standard image. All the other negatives are projected individually by a second projector. The observer varies the magnification until both images show the same graininess. The magnifying factor can be used as a relative measure for the graininess. This test procedure was repeated several years later with different personnel. The films were rated in the same order, but the absolute value between the films differed. The authors decided that this procedure would be suitable only if it was possible to improve the reproducibility through modification of the enlargement and evaluation techniques.

ASTM Committee E-7 decided to keep abreast of any further developments in the international standardization of films[4] and agreed that at the present time a system for film classification was not readily available.

Image Quality Evaluation System

The latest approach being tried is an image quality evaluation procedure that would either form the basis for classification or substantiate one of the previously suggested methods. Essentially, this method uses thin plates with a hundred holes of a given diameter as the resolution test. By varying the hole diameters and the plate thicknesses, equivalent penetrameter sensitivities from 2.5 percent down to 0.94 percent are specified. The evaluation of several sets of radiographs produced in a specified procedure is now underway by radiographic interpreters at several facilities. The committee will gather these data for analysis and decide if a classification system can be based on these results.

Conclusion

After considerable effort, one may ask what are the accomplishments of this committee and perhaps even more basic, is a classification system necessary? The committee feels that a system is necessary to give an indication of potential film performance in a given radiographic system and to differentiate between the films of a given company.

The committee has recognized that a given class of film should not be so narrow that only a single film fits every class, that is, the range should be wide enough to have competitive film. Agreement has been reached on a standardized test procedure in regards to X-ray energies, lead screens, absorbers, method of processing, and use of manufacturers recommended chemistry. What is evident is that film can be classified only if the entire radiographic system is specified carefully. The analysis of the equivalent penetrameter sensitivity obtained in a standard test system may provide the basis for a subjective system of film classification.

[4]Bollen, R. and DeMeester, P. J., "A New Characterization of X-Ray Films," private communication.

Jerry Haskins[1]

Standards for Neutron Radiography

REFERENCE: Haskins, Jerry, "**Standards for Neutron Radiography,**" *Nondestructive Testing Standards—A Review, ASTM STP 624,* Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 108–114.

ABSTRACT: The growth of neutron radiography and the subsequent demand for recommended practices are discussed in terms of their influence on the development of national standards. Included is a discussion of existing standards, an overview of current activities, and a preview of future efforts.

KEY WORDS: nondestructive testing, standards, neutron radiography

The use of neutrons in radiography is a relatively new concept. In general, significant milestones occurred in neutron radiography approximately 45 years after equivalent milestones in X-radiography.[2,3] The most significant exception to this lag is the need for and development of standards.

The first large scale application of neutron radiography[4] was in the Apollo program where the need for standard methods and recommended practices already was recognized. Because of the stringent quality demands on Apollo, immediate pressure was placed on neutron radiography for standards as advanced as those developed over many years in X-radiography. In addition to this pressure, the supporters of the neutron radiography field recognized the relationship between standards and the psychological acceptance of a new field.

Despite the obvious need for standards, it soon became apparent that the task of their development was hindered by three basic factors. The most significant roadblock came from a vocal minority of X-radiog-

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[2]Barton, J. P., *Journal of Materials,* Vol. 7, 1972, pp. 18–24.

[3]Berger, Harold, *Neutron Radiography, Methods, Capabilities, and Applications,* Elsevier, New York, 1965.

[4]*Practical Applications of Neutron Radiography and Gaging, ASTM STP 586,* Harold Berger, Ed., American Society for Testing and Materials, 1976.

raphers. They felt that X-ray standards were adequate, established, and totally applicable to neutron radiography. The other two roadblocks inadvertently supported the goals of the first group. The research-oriented neutron radiographers felt that standards generated by an academic orientation were definitely superior to those biased by commercial interests. Reinforcing this belief was the competition for stature among the commercial suppliers. These varied philosophies contributed little to a unified consensus standard.

In an effort to find a degree of consensus and to provide a forum for communication, a group of neutron radiographers founded the Association of Neutron Radiographers (ANR) under the leadership of Dr. J. P. Barton in 1969. Although some members of the ANR were reluctant to form a new society, there was little choice, because the established societies were not yet ready to recognize neutron radiography formally. Part of this reluctance stemmed from an incompatibility with society charters and part from a concern that neutron radiography was not established well enough to guarantee longevity. Although the ANR has no formal authority to issue standards, it did bring the neutron radiographers together and stimulated efforts toward standardization. Due to pressure exerted by the ANR and the concern of certain key individuals in the American Society for Nondestructive Testing (ASNT) and American Society for Testing and Materials (ASTM), these two societies formally recognized the need for standardization. Efforts in the ASNT were directed toward the establishment of a personnel qualifications (PQ) document for neutron radiography. Under the leadership of Dr. W. L. Whittemore, a PQ document was developed and submitted for inclusion in ASNT Recommended Practice for Nondestructive Testing Personnel Qualification and Certification (SNT-TC-1A) in 1973. Despite approval by the PQ committee, publication was delayed pending revision of the whole SNT-TC-1A document. Publication of the new SNT-TC-1A document produced several positive results. The first of these was the reduced skepticism from many people who believed that any new standards action required a ten to fifteen year effort in a new field. The second result involved increased support from users and suppliers as their confidence in standards activities increased. Finally, the broad general use of the concepts produced a storehouse of ideas for future standards and for improvements of existing approaches.

Concurrent with ASNT activities, neutron radiography supporters succeeded in their efforts to obtain ASTM recognition when, in 1971, E. L. Criscuolo was appointed chairman of Section E07.01.02 on Neutron Radiography of ASTM Committee E-7 on Nondestructive Testing. Under his leadership, several working groups were created to address the questions regarding image quality indicators (IQIs) terminology and recommended practices. Only one of these groups, the IQI Task Force, was successful in its efforts.

The IQI Task Force was composed of a small group of suppliers and users which began its work with a review of existing IQIs and specifications. From these and input from other neutron radiographers, the group defined the parameters desired. A strong emphasis was placed on the need for a new approach as opposed to merely adopting a neutron radiography equivalent of the X-radiography penetrameters. The guidelines for the major goals set forth for the IQI are as follows.

1. It should provide a routine check of radiographic consistency.
2. It should permit the customer to establish minimum quality requirements and have the means to document conformance to these requirements.
3. The IQI should have provisions for both qualitative and quantitative evaluation, that is, both visual and densitometric measurements.
4. It should be fairly small in size, economical to produce, and the analysis of results should require a small amount of time.
5. Results should be expressed in numerical values.
6. If possible, it should allow some degree of beam and problem analysis.

The review of existing techniques shows that each existing IQI met one or more of these criteria but that none met all criteria to the degree desired.

Based upon these requirements, an initial unit was designed and fabricated. The unit consists of two basic parts—beam purity indicator (BPI) as shown in Fig. 1, and four sensitivity indicators as shown in Fig. 2. The BPI consists of two sections of boron nitride and a step block of lead. The boron nitride makes possible measurements regarding the total neutron exposure and the neutron energies and scattering factors involved in

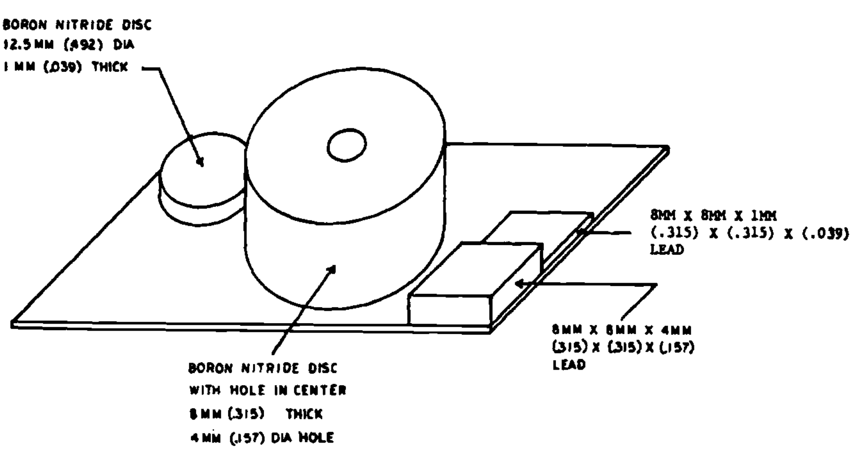

FIG. 1—*Beam purity indicator.*

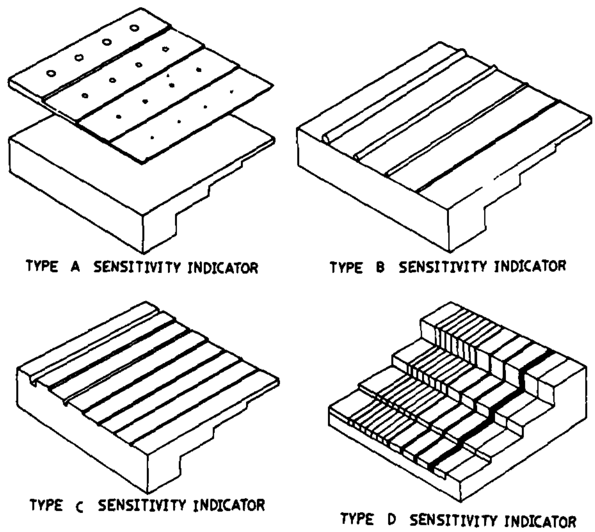

FIG. 2—*Types of sensitivity indicators.*

that exposure. The lead makes possible measurements regarding gamma exposure and its energy. The BPI meets the criteria for quantitative measurements regarding radiographic quality. To meet the criteria calling for visual indications, four plastic step blocks were perturbed by the addition of holes, rods, grooves, and gaps. These four anomalies permit reasonable approximations of the types of anomalies commonly found in components to be neutron radiographed. After initial testing of the IQI, a detailed interlaboratory evaluation was made at all domestic facilities willing to participate.

This detailed evaluation indicated several inconsistencies in the first design of the BPI, so a second design was developed as shown in Fig. 3. Conceptually, the new design was the same except that each of the beam attenuators was surrounded by boron nitride to eliminate the influence of scattered neutrons on the readings. Use of the new PBI design depends upon five densitometric readings to be used in calculating beam constituents. Tabulated in Table 1 are the reading and those beam constituents which are attenuated.

From these five measurements, the percentage of each beam constituent making up the final radiographic image can be determined. Some image components such as film fog, high energy gamma, and high energy neutrons are lumped together in routine analysis. Probably the most important calculation is that which gives the total film exposure produced by collimated, thermal neutrons. It is this number which clearly demonstrates how successful the radiographer is in producing a thermal neutron radiograph. It should be apparent by this time that the IQI itself allows

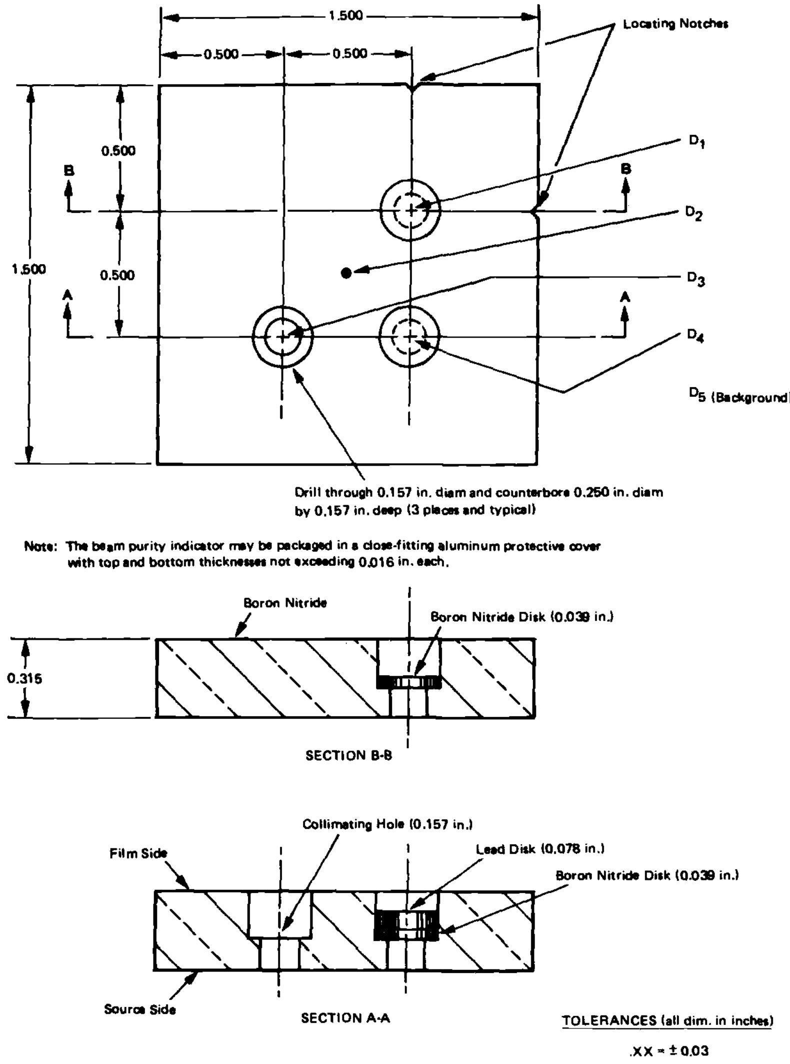

FIG. 3—*Beam purity indicator (all dimensions are in inches).*

no correlation between results obtained from the IQI and the applicability of the neutron radiograph to inspection of a particular component. This correlation can only be made by determining the minimum acceptable BPI readings which result in a useful image for that particular inspection. The use of the sensitivity indicators provides the visual or qualitative reference defined in our list of criteria. Most importantly, however, the sensitivity indicators provide an indication of the combined effects of contrast and

TABLE 1—*Significance of measurements.*

	Attenuator	Beam Constituents Attenuated
D_1	1-mm boron nitride	thermal and scattered neutrons
D_2	8-mm boron nitride	thermal, intermediate, and scattered neutrons
D_3	boron nitride around hole	scattered neutrons
D_4	1-mm boron nitride and 2-mm lead	thermal and scattered neutrons and low energy gamma
D_5	none	none

unsharpness on the sensitivity of detail visible in the neutron radiograph. Reduction of either factor reduces the sensitivity accordingly.

A second interlaboratory evaluation was carried out with the new design. Analysis of these results demonstrated that the basic design criteria had been met. Studies with various film types produced expected quality relationships, and direct correlations between the visual and densitometric values proved the interrelationship between the BPI results and the sensitivity indicator results. Based upon the success of this modification, the concept was submitted for formal ASTM approval and was issued by ASTM in June of 1975.

Current activity in developing consensus standards for neutron radiography centers in ASTM. Current ASNT activity is directed mainly toward the establishment of a uniform method for certifying nondestructive testing (NDT) Level III personnel in all the branches of NDT. ASTM, on the other hand, has increased its recognition of the field by elevating the neutron radiography effort from section status under Subcommittee E07.01 on Radiographic Practice and Penetrameters to full subcommittee status (E07.05 on Neutron Radiography). This move has not only increased the status of neutron radiography but also reduced the burden of balloting neutron radiography documents through the X-radiography subcommittee.

Activities in ASTM Subcommittee E07.05 currently are directed toward refinement of ASTM Determining Image Quality in Thermal Neutron Radiographic Testing (E 545-75), development of a recommended practice for performing neutron radiography, film classifications, and standards for radiography of nuclear fuels. Refinement of ASTM Standard E 545-75 probably will involve the addition of some form of resolution indicator as well as design changes in the BPI which will permit improved analysis of factors which produce the radiographic image. The recommended practice will be similar in scope to ASTM Recommended Practice for Radiographic Testing (E 94-68 (1974)) with reduced emphasis on penetrameters or IQIs. The subcommittee also is attempting to develop a set of educational radiographs to show the areas in which neutron radiography is most applicable. The educational goals of the group were significantly advanced through the National Bureau of Standards (NBS)/ ASTM symposium on Practical Applications of Neutron Radiography and Gaging which was planned so ably and executed under the leadership of Harold Berger in 1975. Not only did the symposium introduce many new people to the field and its applications, but it motivated several key neutron radiographers to join ASTM Subcommittee E07.05 as working contributors. This increased support assures us of a large enough work force to accomplish the large range of tasks set before us.

Without question, the greatest challenge to the neutron radiographers is the development of standards that are appropriate to the needs of neutron radiography and yet are compatible with the format and practices of sister NDT fields. Production use of the ASTM Standard E 545-75 has demonstrated the validity of the IQI system. Acceptance of the document is at a high level with most new aerospace specifications incorporating the approach. Criticism mainly has centered around the need for changes which will allow better characterization of the image and not around its application for production use. However, the quality and enthusiasm of ASTM Subcommittee E07.05 contributors offers promise that the neutron radiographers will be the innovative element in standards development and shift the challenge of compatibility to other NDT methods.

The initial success of standards development in neutron radiography has produced the momentum needed for a strong and continuing program in the field. As the application of neutron radiography expands, this momentum will continue and result in positive responses to the needs of a diverse and growing discipline.

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Status of Reference Radiographs

REFERENCE: Goldspiel, Solomon, "**Status of Reference Radiographs,**" *Nondestructive Testing Standards—A Review, ASTM STP 624,* Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 115–128.

ABSTRACT: The paper summarizes work on reference radiographs over a period of 30 years covering: (*a*) availability and limitations of American Society for Testing and Materials (ASTM) reference radiograph standards, (*b*) some correlation work between radiographic quality and strength, (*c*) problems in mass production of illustrations, and (*d*) projection of work needed in the field in the near future, including considerations to be given to justify the need for new reference radiograph documents for a particular alloy or fabrication type.

KEY WORDS: radiography, nondestructive tests, standards, steel castings, bronze castings, aluminum castings, steels, metals, tests, welded joints

Radiography is one of several nondestructive test methods which has gained early and most common acceptance in quality assurance of metallurgical fabrications, principally castings and welds, because of the apparent simplicity of its readout, the radiograph. A radiograph, in principle, is a simple projection of varying film densities on a single plane produced in theory by a point radiation source placed on one side of the object under examination with the photographic film on the other. Superficially, interpretation of the internal soundness of an item merely requires comparison of the radiograph of each portion with a set of reference radiographs with typical flaw indications of varying severity, which can be used to establish accept-reject limits in contractual considerations.

In reality, however, interpretation of radiographic quality of metallurgical fabrications, such as castings and welds, is much more complicated. It involves development of realistic reference radiograph documents and accept-reject criteria from these. Development of reference radiographs, to be meaningful, must take into consideration many factors, in-

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cluding (*a*) fabrication method, (*b*) alloy type, (*c*) section thickness, (*d*) applicable radiation source type, (*e*) recognition of discontinuity types by cause, (*f*) effect of severity level by discontinuity type on performance, that is, mode and degree of loading in the actual item use, (*g*) method of multiple reproduction of the original set of radiographs chosen for the reference document, and (*h*) the quality level of production radiography compared to those used to make originals in the reference radiographic document set.

This paper is intended to summarize work on reference radiograph documents for a period of about 30 years covering (*a*) availability and limitations of current American Society for Testing and Materials (ASTM) reference radiograph standards, (*b*) some correlation work between radiographic quality and strength, (*c*) problems in mass reproduction of document illustrations, and (*d*) a projection of work needed in the field in the near future, including considerations to be given in determining the need for new documents for a particular alloy and or fabrication type.

The development of ASTM reference radiograph documents and the U.S. Navy's role in such work have been described previously in considerable detail.[2] Briefly, ASTM Reference Radiographs for Steel Castings up to 2 in. (51 mm) in Thickness (formerly E 71-42, now E 446-75) the first tentative reference radiograph document adopted by ASTM, used a set of radiographs which formed part of a steel casting radiographic acceptance standard (Radiographic Standards for Steel Castings (NAVSHIPS 250-692-13)) developed by the U.S. Navy for its own use in 1942. This set, consisting of selected production radiographs of steel castings with typical discontinuities of varying severity levels on basis of judgement unbacked by actual data, served for many years in judging radiographic quality of common alloy castings for important service. Their use led to the recognition that (*a*) castings from which "reference" radiographs are made should be available and stored for possible future use, for example, in checking improvements in detection which new radiographic sources, techniques, and recording media may make possible; (*b*) radiographs used as references, and hence for accept-reject criteria, should be related to cause of flaws and to deterioration of engineering properties with increased severity of various discontinuity types; and (*c*) different alloy types and fabrication methods often involve discontinuity types not commonly found in low alloy steel castings.

[2] Goldspiel, S., "Development of Radiographic Standards for Castings," *Proceedings*, Fifth International Conference on Nondestructive Testing, Montreal, Canada, 1967; a portion of this paper appeared in *Materials Research and Standards*, Vol. 9, No. 7, 1969, p. 13.

Available Reference Radiograph Documents

As a result of considerable effort, much cooperation of industry and accelerated by help from U.S. Navy project work, ASTM has developed a series of reference radiograph documents covering common alloy casting types and steel fusion welds. The following is a brief description of the currently available documents which also will be used to illustrate factors differentiating them.

Steel castings reference radiographs are covered by four documents. Three of these, summarized in Table 1, apply to sand castings of all types and are differentiated among each other on the basis of applicable section thickness and, hence, the radiation source types which can be properly used to make production inspection radiographs. ASTM Reference Radiograph E 446-75, the newest of the three documents and a replacement of ASTM Reference Radiograph E 71, applies to castings with sections up to 2 in. and comes in three sets representing commonly used radiation source types. The heavier section castings are covered by ASTM Reference Radiographs for Heavy-Walled (2 to 4½-in. (51 to 114-mm)) Steel Castings (E 186-75) and ASTM Reference Radiographs for Heavy Walled (4½ to 12-in. (114 to 305-mm)) Steel Castings (E 280-75). For all three documents, references include graded types, where the flaws which they represent may vary in extent, depending on the critical nature of the casting service. They also contain illustrations of ungraded flaws which are either inadmissible at all or which are used to illustrate conditions otherwise not clearly recognized. The use of sets for more than one radiation source type often is based on the fact that contrast, all other factors remaining constant, differs with the penetrating source energy. The fourth steel casting document, summarized in Table 2, is ASTM Reference Radiographs of Investment Steel Castings for Aerospace Applications (E 192-75) which applies to relatively thin castings for highly critical applications, such as aerospace. As a matter of fact, the document also includes in its title the word "Investment," which was intended to point to the fact that some castings used to produce the original set of radiographs were made by this process. It may be noted that this set of references includes mold and core defects and diffraction effects which are peculiar to investment castings and thin sections, respectively.

Aluminum and magnesium casting reference radiographs are covered by ASTM Reference Radiographs for Inspection of Aluminum and Magnesium Castings, Series III (E 155-76) for sand and ASTM Reference Radiographs for Inspection of Aluminum and Magnesium Die Castings (E 505-75) for die castings, Tables 3 and 4 respectively. Many of the discontinuity types in ASTM Reference Radiograph E 155-76 are similar to those for steel castings. The principle differences in this document are

TABLE 1—*ASTM Reference Radiographs E 446-75, E 186-75, and E 280-75, steel castings, number of grades.*

Document		E 446-75			E 186-75			E 280-75	
Applicable steel sections, in.		up to 2			2 to 4½			4½ to 12	
Radiation sources		250 X-rays	1-MV X-rays, and Ir 192	2 to 4-MV X-rays, Co60	1-MV X-rays, Ir 192	2 to 4-MV X-rays, Co60	4 to 30-MV X-rays	2-MV X-rays, Co60	4 to 30-MV X-rays
Porosity		5	5	5	5	5	5	5	5
Sand inclusions		5	5	5	5	5	5	5	5
shrinkage types	1	5	5	5	5	5	5	5	5
	2	5	5	5	5	5	5	5	5
	3	5	5	5	5	5	5	5	5
	4	5	5	5	...	...	...	...	...
Crack		1	1	1	1	1	1	...	...
Hot tear		1	1	1	1	1	1	1	1
Insert		1	1	1	1	1	1	1	1
Mottling		1	1	1	...	...	...	...	...

TABLE 2—*ASTM Reference Radiograph E 192-75, applicable to ¼ to 1-in. sections, 130 to 150 kV X-ray radiation source.*

Grade, 6 each		
Type	Section, in.	Ungraded Types ⅜-in. Sections, 1 each
Gas holes	⅛	hot tear
	⅜	hot tear
	¾	cold crack
Shrinkage		
cavity	¾	cold shut
	⅛	misrun
sponge	⅜	mold, buckle, positive
	¾	mold, buckle, negative
dendritic	⅛	mold, ridge
	⅜	core, shift
	¾	core, excess metal in crack of
filamentary	¾	
Foreign material, less dense	⅛	diffraction pattern, columnar
	⅜	diffraction pattern, mottled
	¾	foreign material, more dense

TABLE 3—*ASTM Reference Radiograph E 155-76, applicable to ½ to 2-in. sections, number of grades.*

Aluminum			Magnesium[a]		
	Number for Thickness, in.			Number for Thickness, in.	
Discontinuity Type	¼	¾	Discontinuity Type	¼	¾
Gas hole	8	8	gas holes (1)	8	8
Gas porosity					
round	8	8	gravity segregation (2)	8	...
elongated	8	8			
Shrinkage			microshrinkage		
cavity	8	...	feathery	8	8
sponge	8	8	sponge	8	8
Foreign material			foreign material		
less dense	8	8	less dense	8	8
more dense	8	8	more dense	8	8
			reacted inclusions (3)	8	...
			eutectic segregation (4)		
			microshrinkage	1	...
			pipe, hot-tear, flow line	1	...

[a] See footnote 3 of paper.

NOTES—All aluminum plates were 356 type; (1) ZK51A; (2) ZK91; (3) HK31A; (4) EZ33A; all others AZ91C.

TABLE 4—*ASTM Reference Radiograph E 505-75, applicable to 1-in. sections, low energy X-rays.*

		Number of Grades			
		Aluminum, in.		Magnesium, in.	
Category	Description	⅛	⅝	⅛	⅝
A	round or elongated dark spots, single or in clusters	4	4	4	4
B	linear inclusions, with smooth outline, continuous or interconnected	4	4	4	4
C	filamentary or jagged, continuous or interconnected	4	4	4	4
D	irregular inclusions, lighter or darker: oxides, dross, or metallic	...	1[a]	1	...

[a] Thickness of plate was 0.20 in.

that (*a*) the light metals and thin sections involve low energy X-ray sources which produce high contrast radiographs, differing considerably in appearance with relatively small changes in thickness of section traversed, (*b*) solidification phenomena, especially in magnesium alloys with heavy metal alloying elements, produce peculiar appearing discontinuities such as gravity and eutectic segregations, and (*c*) foreign inclusions come in both less and more dense form types. These peculiarities are described from a metallurgical point of view in detail by Lagowski.[3] The discontinuities for aluminum and magnesium die castings are so peculiar to the fabrication process that they merely are referred to by category, letter, followed by rather detailed description of their appearance on the films.

Copper and copper-nickel base alloy castings are covered by ASTM Reference Radiographs for High-Strength Copper-Base and Nickel-Copper Alloy Castings (E 272-67(1973)) and ASTM Reference Radiographs for Tin Bronze Castings (E 310-68(1974)) (see Table 5). The former represents high strength, relatively narrow solidification alloy types, such as manganese-nickel-aluminum bronzes and copper-nickels. The latter document represents tin bronzes or wide solidification types. The high absorption elements and differing solidification modes considerably influence the characteristic appearance of the common radiographic flaw indications of the two alloys. In addition, the higher strength alloy types, which often are cast also to thick sections, require references made by radiation source types of decidedly different penetration capability. This accounts for using 1 and 3-in. plate castings for producing the radiograph illustrations. In addition, the thickness of sections and projection effects cause certain shrinkage types to appear feathery in the thinner sections

[3] Lagowski, B., *Journal of Testing and Evaluation*, Vol. 2, No. 4, 1974, p. 221.

TABLE 5—*ASTM Reference Radiographs E 272-75 and E 310-70, copper and copper-nickel alloy castings, number of grades.*

Applicable Alloys	High Strength Cu and Cu-Ni Castings		Tin Bronze Castings
Reference Casting Sections	1-in. Plates	3-in. Plates	¾ and 1-in. Plates
Radiation source	Low Voltage X-Ray	2 MV X-Rays and Co-60	Low Voltage X-Rays
Applicable Section Thickness	to 2 in.	2 to 6 in.	to 2 in.
Gas porosity	5	5	5
Inclusion			
sand	5	5	5[a]
dross	5	5	...
Shrinkage			
linear	...	5	5
feathery	5	...	5
sponge	...	5	1
Hot tear	...	...	1[a]
Insert	...	...	1[a]

[a] Make from ¾-in. plate castings.

and spongy in the thicker sections. The individual, unacceptable hot tear and insert flaws may apply to both alloy types, although they are more frequently encountered in tin bronze types.

Fusion welds for steel are covered by ASTM Reference Radiographs for Steel Fusion Welds (E 390-75) summarized in Table 6. This document covers seven thickness ranges from sections of 30 mils to 8 in. and, hence, includes radiographic illustrations for commonly corresponding radiation source types. Again, as for the steel castings, the flaws are shown in graded types and as single illustrations. The latter are mostly to assist in recognition of discontinuity types, such as cracks which are not admissible in quality welding.

Limitations of Reference Radiograph Documents

The limitations of all the documents mentioned here is that even their graded illustrations cannot cover all situations encountered in actual production radiography. Thus, for example, in illustrating porosity of a particular severity, one can show illustrations which differ in size, distribution, and darkness of individual indications. Actually, knowledgeable radiographic interpreters must balance numbers, distribution, and sizes by judging their probable collective effect on strength. Darkness of indications often cannot be considered at all in severity determinations, because darkness, especially in heavy sections, is a function of flaw depth and hence of the radiation projection. Similar considerations apply to judging

TABLE 6—*ASTM Reference Radiograph E 390-75, number of grades.*

Base Material Thickness (in.)	0.030	0.080	3/16	3/8	3/4	2	5
kV X-Rays Used	90	120	150	175	250	2MV; Co60	2MV; Co60
Applicable Sections	to 0.50	to 1/8	1/8 to 1/4	1/4 to 1/2	1/2 to 1 1/2	1 1/2 to 2	3 to 8
Discontinuity type							
porosity							
scattered	...	...	...	...	...	...	5
fine scattered	5	5	5	5	5	5	...
coarse scattered	5	5	5	5	5	5	...
clustered	5	5	5	5	5	5	5
linear (globular)	5	5	5	5	5	5	5
elongated (worm hole)	...[a]	...	...[a]	...[a]	...[a]	...[a]	...
inclusions							
slag	...	5	5	5	5	5	5
tungsten	5	5	5	5	5	5	...
incomplete penetration	...	...[a]	5	5	5	5	5
lack of fusion	...[a]	...	5	5	5	5	5
burn through	...[a]	...	...[a]	...[a]	...[a]	...[a]	...
icicles (tear drops)	...[a]	...	...[a]	...[a]	...[a]	...[a]	...
cracks							
longitudinal	...	...[a]	...[a]	...[a]	...[a]	...[a]	...[a]
transverse	...[a]	...	...[a]	...[a]	...[a]	...[a]	...[a]
crater	...[a]	...	...[a]	...[a]	...[a]	...[a]	...
undercut	...[a]	...	...[a]	...[a]	...[a]	...[a]	...

[a] Ungraded discontinuity types.

other discontinuity types. Linear shrinkage types must be judged not only on basis of length but also on the degree of stress concentration they represent. Very often, the question to be answered by the interpreter in judging a production radiograph versus a reference accept-reject illustration is "which would be more damaging?" In this type of interpretation, past experience with the fabrication types, based on "opening up" of castings or welds in repairs, is of invaluable assistance. Very often, however, additional exploratory and diagnostic radiography are necessary for more definitive resolution of doubts.

Current reference radiograph document illustrations also are limited by the fact that the graded severities for various types are somewhat arbitrary and do not change in a definite way for related documents. Thus, Severity Level 2 for ASTM Reference Radiographs E 186-75 and E 280-75 necessarily do not show comparable degradation in casting quality. Severity Level 2 of porosity or shrinkage in the same document has no known relationship to each other. The reasons for this condition are easy to understand though difficult to overcome. For castings, documents, for example, representing eight out of nine ASTM reference radiographs documents, plate castings with various discontinuity types are prepared by deliberately planned faults in foundry practice or solidifaction conditions. Yet, there are so many uncontrollable influences in casting that it takes many castings before a predetermined type and severity flaw is achieved in practice. Hence for economic reasons, the number of ultimately chosen plate castings reflects much to be desired in way of uniform gradation of severities.

The limitations of the published documents became clear when an effort was made to compare illustrations of new documents to ones previously available and specified. When ASTM Reference Radiographs E 186-75 and E 280-75, for 2 to 4½-in. steel sections and 4¼ to 12-in. sections, respectively, were published, severity levels of the new documents had to be somehow related to those of ASTM-Reference Radiographs E 71 heretofore used for all section thicknesses. Work to correlate the severities of the new documents with the grades of the ones they replace showed that at best only approximate correlation was possible.[4] A similar conclusion appears to be developing from a more recent effort to establish a comparison of casting severity levels in ASTM Reference Radiographs E 446-75 with E 71 which it replaces. The practical result of recognizing limitations of severity gradations of various discontinuity types within a document and between documents is for specification engineers to refrain from using the same severity level for each type but to call out the severity judged most applicable to the particular application. The justification of this approach is upheld also by correlation work between

[4] ASTM Ad Hoc Committee on Correlation of Reference Radiographs for Steel Castings, *Materials Research and Standards*, Vol. 9, No. 5, 1969, p. 14.

radiographic flaw indications of various types and severities with their effect on mechanical properties.

Correlation Work between Radiographic Quality and Strength

Correlation between radiographic quality and strength of castings or welds, while most important in arriving accept-reject criteria, is an area which has to date been neglected most. Before a brief summary is given of the work in the area, it might be well to point up that (*a*) soundness quality is often specified more on a basis of what may be achieved with known good practice rather than on effects on ultimate strength in the particular application, and (*b*) radiographic quality alone, without regard to other test indications, even in theory cannot provide adequate assurance for adequacy of strength in a particular application. Thus, very simply, within reason, radiography at best can provide the confidence in soundness the way compliance of a casting test coupon to composition and mechanical test requirements can to confidence in the casting it represents.

Work on correlation of static tensile properties with severity of radiographic discontinuities of various types for Class B steel complying with Military Specifications for Steel Castings (MIL-S-15083) and manganese-nickel-aluminum alloy #2 bronze complying with requirements of Military Specification, Bronze, Nickel, Aluminum and Manganese-Nickel Aluminum, (MIL-B-21230) (see footnote 2) led to the following conclusions.

1. Visual graduation of radiographic indications for steel castings yields severity levels which gave linear regressions with respect to ultimate strength for all defect types, except inclusions.
2. The deterioration in ultimate strength of steel in the annealed condition may be estimated from the severity of radiographic indications. The deterioration is most severe for linearly disposed discontinuities, such as shrinkage.
3. The yield point is practically unrelated to the severity of radiographic indications within the range studied, except for the most severe levels of the linear type.
4. Ductility of cast steel is affected drastically by soundness and cleanliness. Where elongation is important in design, the quality of steel castings is dictated by this parameter.
5. While radiographs of castings should by no means be used to replace tension testing, the static tensile strength of particular portions may be assessed with considerable confidence by use of relationships shown in Table 7.

Similar, though fewer data for the manganese-nickel-aluminum bronze castings (see footnote 2) led to the following conclusions.

1. The general trends for steel are verified.

TABLE 7—*Statistical correlation data between tensile properties and severity of representative types of radiographic indications in 3-in.-thick steel and manganese-nickel-aluminum bronze plate castings.*

Material	Discontinuity Type	Tensile, 1000 psi		Yield, 1000 psi		% Elongation, 4-in. gage length	
		Slope	95% Tolerance Limit	Slope	95% Tolerance Limit	Slope	95% Tolerance Limit
MIL-S-15083 Class B steel (3-in-thick steel)	gas porosity, A	−3.28	±5.2	−0.43	...[a]	−3.65	±5.0
	inclusions, B	−0.03	...[a]	−0.03	...[a]	−1.36	...[a]
	shrinkage						
	linear, Ca	−8.11	±6.2	−1.76	±2.3	−3.38	±4.8
	dendritic, Cb	−8.11	±9.2	−0.69	±3.0	−1.22	±3.8
	warm hole, Cc	−7.60	±5.4	−1.43	±2.2	−3.46	±5.6
	hot tears, D	−8.06	±6.8	−1.23	±2.0	−4.40	±5.8
	inserts						
	chills, Ea	−2.58	±5.2	−0.08	...[a]	−2.59	±4.3
	chaplets, Eb	−4.93	±5.4	−0.06	±1.9	−3.26	±3.8
MIL-B-21250 A Alloy No. 2 (magnesium-nickel-bronze plate castings)	gas porosity, A	−4.07	±6.4	...[b]	...[b]	...[a]	...[a]
	inclusions						
	sand, Ba	−0.06	±7.2	...[b]	...[b]	...[a]	...[a]
	dross, Bb	−3.85	±9.0	...[b]	...[b]	...[a]	...[a]
	shrinkage						
	linear Ca	−3.62	±8.4	...[b]	...[b]	−1.10	±2.6
	spongy Cd	−3.58	±10.1	...[b]	...[b]	−0.93	−3.0

[a] No significant relationship indicated.
[b] Data not taken.

2. Slopes for most curves are somewhat smaller than for steel, possibly due to (*a*) nonequivalence of the severity levels for the reference radiographs of the two materials and (*b*) relatively lower notch sensitivity of the bronze.

An attempt to develop correlation between radiographic severity level for various discontinuity types and flexural resistance for the materials just cited in the discussion of static tensile work, gave negative results. Of all discontinuity types considered, gas porosity in steel castings appears to be most detrimental to the ability of the material to resist flexural energy. For all discontinuity types, location of the defect with respect to the tension surface is more important than the extent, as shown in plan radiographs evaluated with reference radiographs in a conventional manner. In short, this failure of radiography is mainly attributable to its inability to evaluate depth of defects, especially near the surface.

The important conclusion from the correlation work summarized here is that performance of castings in flexure cannot be assessed reliably with radiography alone as it is used usually. For flexural loading, greater reliance must be placed on those nondestructive testing methods which evaluate surface and near subsurface discontinuity types.

Problems in Mass Production of Reference Radiograph Illustrations

Effective work on reference radiograph documents, considering their benefits as well as limitations, must take adequately into consideration the proper mass reproduction of illustrations. In general, mass reproduction of illustrations may be accomplished in two ways. For light metals and thinner sections of the heavier common metal types, ASTM has been using actual radiographs produced under conditions which provide closely controlled contrast and base density. For steel and bronzes, and in all but very thin sections, mass reproduction utilizes special direct positive films. To achieve authentic rendition of the originals as far as contrast and base density are concerned, the emulsion must be pretested to determine the useable range under a particular set of parameters. In addition, since direct positive films generally do not attain the H & D density of many radiographs, the properly processed direct positive film copies are often backed by neutral filters. The resulting product, when direct positive films are used in making mass production reference radiograph illustrations, is a combination of a direct positive copy plus a uniform density filter which yields a combined base density practically equal to that of the original radiograph. This procedure is dictated by prohibitive costs of shipping of heavy original plates and their actual radiography. Close monitoring of every illustration is essential for production of reference documents. This entails, at the present time, voluntary expertise provided to the monitoring operations by a relatively small and highly knowledgable group of people every time a quantity of documents is issued.

Work Needed in the Field in the Near Future

From time to time, ASTM is required to consider work on new reference radiographs. This is based on the advent of new materials, new excitation source types, extension of section thicknesses used by industry etc., all of which could produce indications not covered adequately by existing documents. Work in this area still in progress at this time involves gray and ductile iron castings and titanium alloy castings and welds. For the gray iron castings, the work is almost completed and shows that addition of a type of shrinkage, known as feathery, to existing references for steel castings, depending on section thickness, should cover the present need adequately.

The work on titanium alloys, originally directed at developing needed references for both castings and welds, has stopped recently within ASTM because of inadequate support from industries involved. At any rate, work on welds accomplished to date has shown that for most common welding processes the steel fusion welds are adequate. Limited work on reference radiographs for castings is reportedly now in progress under aerospace industry sponsorship. An increase in industrial activity in titanium castings, with time, may revive a corresponding interest in ASTM reference radiographs for these materials.

By far the greatest need for additional work is in the area of providing more quantitive meaning, if possible, to the use of reference radiographs as accept-reject criteria in castings and welds for critical applications. This work is expensive and to be effective needs sponsorship of a neutral type, so that the results are beyond question. In the long run, considering the potential waste in cases where radiography requirements are unnecessarily demanding or the potential danger in cases where radiography requirements are unnecessarily lenient, the correlation work is justified. Sponsorship of such work perhaps may be motivated when more objective quantitative readout equipment is developed for radiography. That this is not a dream is evident from developments in metallographic equipment where estimation of second phases is already a reality.

Factors to be Considered in Determining Need for a New Reference Radiograph Document

Factors which justify a new reference radiograph document have been cited in the introduction and illustrated in the review of available ones. Each of these should be weighed in a decision involving a new document. However, answers to the following two questions are most important to a decision. These are: (*a*) why will existing documents not suffice and (*b*) what is the minimum addendum required to available documents, which will adequately cover the new material, thickness range, fabrication type, or a combination of these factors? A deliberate decision is essential in order to minimize unnecessary proliferation of documents and costs to all concerned which they entail.

Conclusion

It may be concluded that the present series of ASTM reference radiograph documents, though filling a definite need in the radiography of common metallurgical fabrications, could be improved further by a careful study of the quantitative meaning of various types and severities of flaw indications they show. Proliferation of documents without due justification should be avoided.

J. E. Bobbin[1]

Ultrasonic Testing Standards—Overview

REFERENCE: Bobbin, J. E., "**Ultrasonic Testing Standards—Overview,**" *Nondestructive Testing Standards—A Review, ASTM STP 624,* Harold Berger Ed., American Society for Testing and Materials, 1977, pp. 129–132.

ABSTRACT: Ultrasonic testing is used extensively for flaw detection, thickness measurement, and determining material properties. Now, as the field reaches maturity, there is a greater need to obtain quantitative data from the test itself. This need, in turn, has been followed by an implied need for standardization.

The goal of standardization, for whatever reasons, is laudable. In ultrasonics it covers three possible areas of interest which will be discussed in detail in the following papers. These include: the instrumentation itself, including probes, and the possible standardization of performance characteristics; reference standards including test blocks and other techniques for setting rejection limits; and finally standarization of application techniques.

Our challenge is first to determine what should be standardized within each area. Then, under what conditions should such standards be applied. The developers of these standards should also clearly understand the complex relationship between the significance of the parameters being standardized, the performance flexibility of the equipment, and the overall cost/benefits involved.

This presentation attempts to put some of these factors into proper perspective, so that realistic standardization may benefit all parties concerned.

KEY WORDS: nondestructive testing, standards, ultrasonic tests

The growth of ultrasonic testing as an extremely versatile technique for flaw detection, thickness measurement, and determining material properties has been substantial. For the past thirty years, equipment has been produced to satisfy three basic tasks of ultrasonic flaw detection: detection of discontinuities, location of the discontinuities, and provision of data to permit evaluation of these discontinuities.

Uses of Ultrasonic Nondestructive Testing

The materials to be tested can be categorized in various ways. New

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material must be determined to be free of detrimental defects. In many instances, the material is pushed to its limits and, therefore, must meet certain performance specifications. Materials engineers are also under constant pressure to provide economical products, while at the same time being faced with the specter of product liability.

Other approaches to material quality requirements include fracture mechanic studies that define certain allowable defects of a critical size. For this, the inspector must be able to define discontinuities as to size, type, geometry, and orientation relative to principal stress directions. Low temperature brittle fracture and high temperature crack growth studies also require additional information from the nondestructive test (NDT).

Ultrasonic equipment also is assigned the task of inspecting used materials from a maintenance standpoint. This can help to avoid failure and also to avoid premature replacement or repair of parts subject to deterioration. In this area, acoustic emission also is helping to determine defect starting point and growth although it still is somewhat qualitative.

Corrosion thickness measurements were one of the earliest uses of ultrasonics. Presently, work is done at high temperature without shutting down the process equipment. Fatigue cracks in many types of machinery, aircraft structures, and the electric power rotor and generator components are tested routinely. Present in-service inspection of nuclear reactor vessels brings very high requirements to maintenance inspection.

Another area in which ultrasonic NDT provides important information is the determination of material properties. Various properties can be related theoretically or empirically to ultrasonic measurements of attenuation, velocity, and combinations of these. Work is progressing in the field, and routine production tests are being done on powdered metal parts, nodular iron castings, and reinforced plastics.

Need for Standardization

In the performance of these inspection tasks, the goal now is for quantitative NDT. From the standpoint of both equipment and methods, we seek uniformity of results.

In many cases, the NDT equipment is being pushed to its limits, relative to the sensitivity to small defects, and ultrasonic penetration to permit the testing of many different materials. Quantitative methods require that the test problem be defined properly and completely to permit selection of the most effective technique for solving it. While the basic requirements remain the same, new developments with demands from the standpoint of productivity, automatic inspection, and computerization put substantial pressures on the industry to improve the quantitative aspects of the test.

For various reasons, the demands become greater that the equipment should be standardized. Some of the following points will be covered in detail by the other authors in this publication.

Ultrasonic Equipment Specifications

When we consider product specifications, whether it be the metal that is being tested or the instrument doing the testing, we can categorize the specification into two groups, design and performance. A design specification sets limiting values on the design or the constituents of the product. In many cases, this inhibits innovation and can lead to somewhat undesirable uniformity.

Performance specifications set limiting values on how a given product will behave under certain stated conditions. In effect, this sets the goals of performance by allowing the user to include his own ingenuity in determining the method of the achievement, and ultimately this also tends to promote innovation in products.

From the standpoint of equipment specifications we then ask the following questions.

1. Will it perform a particular test application? This implies suitable performance of the equipment, technique, and the personnel using the equipment, since these three main components cannot be isolated completely.

2. Which operating or electrical parameters, techniques, and personnel requirements should be controlled in order to assure this performance?

From the standpoint of equipment characteristics, a few of the more important are sensitivity, resolution, and linearity. Sensitivity defines the minimum defect size which can be detected under specified conditions. It is quite material dependent from the standpoint of signal-to-noise ratio. Resolution in the time domain is needed for thickness measurements, to detect small flaws near a large boundary surface, or to separate two small echoes close together in time. It is also important to assist in defect identification which is essential in such areas as fracture mechanics. Linearity from both the time and amplitude standpoint is necessary for proper measurements of echo signals in the task of evaluating the possible defect. It should be remembered that these characteristics can be defined and partially measured independently, but also they may be mutually dependent.

All of these characteristics pose a dilemma not only to the user of the equipment, but perhaps more so to the instrument manufacturers. Recent developments in the instrumentation, primarily from incorporation of newer electronic elements, have improved the portability of the instrument allowing us to get more performance in a small space. Greater production speed and improved productivity have resulted from the expanded use of multiple channel instrumentation.

The output of the ultrasonic test may be an electrical signal which can be recorded for later evaluation or for more permanent storage of the test data. And, finally, combining the ultrasonic instrumentation with computer technology greatly improves the quality of automatic evaluation of discontinuities.

If we follow the requests of some, aimed at standardization of the equipment, the question becomes how to meet all the various material and product specifications for which ultrasonics is presently providing a useful inspection tool. We ultimately would have an incredibly complex single standardized equipment or an infinite number of simple single-purpose devices.

Conclusion

Rather than standardizing the equipment, many national and international groups are approaching the task of standardizing the methods to evaluate the equipment. Defining and measuring characteristics such as the previously mentioned sensitivity, resolution, and linearity, and additional factors, such as the repeatability characteristics, seems to me to be much more practical.

In this regard, there is a major task of educating the NDT community in the real meaning of these various performance characteristics. We also must teach the user to approach test problems from the application requirements based on the detection, location, and evaluation of defects rather than trying to fit these requirements into a single standardized test equipment.

We must use what we have, but use it properly. This necessitates knowing the equipment, both its capabilities and limitations. Also, this requires a study of the test problem and the determination of a suitable technique for the task itself. It also implies that there should be reasonable standards for the material being tested. With this combination of factors, we would be in a much better situation to provide ultrasonic testing to industry.

J. T. McElroy[1]

Search Unit Standardization

REFERENCE: McElroy, J. T., "**Search Unit Standardization,**" *Nondestructive Testing Standards—A Review, ASTM STP 624,* Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 133–137.

ABSTRACT: The search unit, an important component in the ultrasonic examination system, has yet to be controlled by a performance standard. While controversy over methods of measuring performance exist and parameters have not been defined, nevertheless, a foundation document can and must be generated.

KEY WORDS: nondestructive tests, standards, ultrasonic tests, search unit performance standards

The search unit is an important component in the ultrasonic examination system. As the transmitter and receiver of the ultrasonic energy used to interrogate the material under examination, its operating characteristics directly effect the examination results. To ensure the quality of the examination, the repeatability of examination results, and the uniformity of examinations conducted day to day and from site to site, standardization of search unit performance is a critical necessity, and, logically, equipment used to examine material ultrasonically to conform to regulatory codes, specifications, or standards should be controlled by some specification or standard of performance.

Automated and mechanized ultrasonic examination systems are common today. Sophisticated data acquisition systems—some complete with computer data analysis and graphic print out—are becoming more common. It would follow, simply from an economical point of view, that the system's primary sensor, the search unit, be subject to standards governing some minimum value of performance. If its performance is substandard, the examination performed most certainly will be substandard, and the cost of an extensive data acquisition system has been worthless. Unfortunately, despite the obvious need for search unit standardization, an industry-wide document that addresses such standardization has not been developed.

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Present Status of Search Unit Standards

While no industry-wide standards are in existence today, during the past 20 years a great deal of work to develop and implement the examination technique for monitoring search unit performance has taken place. This work has been conducted by many extremely competent individuals in various areas of industry. Although some documents have resulted from this effort, most are still in draft form, and, in all cases, they are addressed to a specific industry area or special interest group. One example of such a document is a guideline for controlling the performance of ultrasonic flaw detection instruments and search units being prepared over the past three years by the Pressure Vessel Research Committee of the Welding Research Council. This document is still in draft form. Other examples are as follows.

1. Society of Automotive Engineers Aerospace Standard for Ultrasonic Transducers, Immersion and Contact, Performance Parameters (SAE 1355).
2. American Society for Testing and Materials (ASTM) Committee E-4 on Metallography, Subcommittee E04.09 on Inclusions, Recommended Practice for the Detection of Large Inclusions in Bearing Quality Steel by the Ultrasonic Method (E 588-76). Appendix A of this document is a detailed specification for the search units used in this application.

Perhaps the longest continuous effort has been conducted by ASTM Subcommittee E07.06.09A on Standardization Procedures for Search Units. This task group has been working toward a document for several years. A vast amount of data and many recommended procedures have been generated; however, to date, a draft of their document has not been balloted.

Where the Difficulties Occur

One of the difficulties in establishing a search unit standard occurs because different industries have different needs. Experience has shown that a proposed search unit standard generated by airframe or aerospace industry interests would not be acceptable to the steel and heavy manufacturing industry and vice versa. In addition, today there is a vast diversity in ultrasonic examination techniques. To keep pace with this diversity, transducers and search unit assemblies are produced with literally hundreds of varying configurations and operating parameters. Within a common search unit size and frequency are gradations of specified performance designed to meet particular test applications. For instance, a search unit of given size and frequency is available in designed variations for the following specific types of service.

1. Highly damped (low Q)[2]
   For thin section thickness measuring
2. Normally damped (medium Q)
   For general thinner section flaw detection
3. Lightly damped (high Q)
   For course grained or thick section flaw detection or both
4. For immersion service, nonfocused for general flaw detection applications or focused for specific material distances

All of these variations would require individual attention in a regulatory search unit standard document for industry-wide application.

The methods used to measure and define a search unit's performance have been a source of controversy. When in actual nondestructive testing service, the transducer always is damped to some degree by mass loading. This damping lowers the natural Q of the piezoelectric transducer, widens its band width, and renders it a rather passive device. Its performance characteristics will be influenced by the wave shape of the driving voltage applied. Also, the characteristics of the receiver, bandpass, linearity, dynamic range, and so forth will effect the measured properties of the search unit. In view of these circumstances, it is apparent that the instrumentation used to assess search unit performance must be specified and controlled.

Controversy about the method of performing assessment comes from two schools of thought. One group insists that laboratory instrumentation, oscilloscopes, pulsers, radio-frequency signal generators, and so forth are the only acceptable methods of measuring transducer performance. Data produced by these methods agree more closely with the theoretical performance predictable for search units of a given size, frequency, and design. The instruments used also can be maintained in a calibrated state to references traceable to the National Bureau of Standards, and the examination results can be expressed in basic units of measure.

The other school of thought insists that the search unit must be assessed by use of typical flaw detection instrumentation used by industry in their nondestructive examination operations. By so doing, the data produced would be directly applicable to their work, and they also would be equipped by use of their individual flaw detection instrumentation to recheck the performance of their search units.

There are certainly reasons to sympathize with both schools of thought. With methods establishing the use of laboratory type instrumentation, the technical base of the standard would be in close agreement with the theoretical and thus would be strong and durable with respect to time. However, it would make most organizations unable to monitor their search

[2] Q = bandwidth/frequency.

unit performance in house and, in some cases, unable to understand and utilize the data pertaining to their search units.

The problems with assessing search unit performance using commercial flaw detection instrumentation are that no standardized design criteria for these instruments are available and their operating characteristics are widely varied. The data identifying search unit performance recorded on one flaw detection instrument might differ greatly from the data recorded for the same search unit on a different make or model flaw detection instrument.

However, standardization of ultrasonic instruments is being addressed by a number of technical groups. With successful completion and implementation of a control document of this type, flaw detection instrumentation could be used more successfully in measuring a search unit's performance. It would certainly be highly desirable to base the search unit's acceptable performance on the data generated by the same instrument that would be used to conduct the nondestructive examination.

Search Unit Operating Characteristics that must be Controlled by Standardization

The intent of this paper is not to discuss in depth the complexities of search unit operating characteristics and the techniques by which they can be measured. Published research contains an abundance of detailed descriptions of search unit operating parameters and recommended methods of measurement. Instead, this paper is concerned with those search unit operating characteristics that necessitate standardization.

Fundamental values of performance dictate the selection of a search unit for a particular ultrasonic examination. The technical format of an examination procedure is based on and relies on these minimum performance values. The ability of the ultrasonic method to perform a volumetric examination relies upon a directive beam of known geometry, beam spread, and wavelength. In view of this, the following operating parameters, as a minimum, must be controlled by standardization:

1. Frequency
2. Size, that is, effective area of the piezoelectric element
3. Beam geometry, that is, axial pressure distribution and cross sectional symmetry of the beam
4. Damping factor and band width
5. Conversion efficiency, that is, loop sensitivity
6. Electrical impedance
7. Refracted angle, for angle beam search units or accessory wedges

A valuable assessment of a search unit's performance is a plot of the emitted beam geometry. A curve representing the received signal amplitude with respect to distance traveled in the propagation medium will describe the axial pressure distribution of the beam. Characteristic points along this curve, such as the far field peak, are predictable and are governed by the size and frequency of the search unit and the velocity of sound in the medium. Transverse plots of the beam at specific points along the distance versus amplitude curve will describe the cross sectional symmetry of the beam.

Conclusions

It is apparent that the immediate need is a concentrated effort in generating a basic search unit standardization document. Technology is available to formulate a meaningful document establishing minimum performance values for at least the most common search unit sizes, frequency, and types.

Until a foundation document is generated and implemented, the evolutionary process toward the ultimate document will never start. This method of first writing a foundation document is standard procedure within technology. All regulatory codes and standards are the result of a continuous evolutionary process of revisions, deletions, and additions attempting to improve the use of the document.

As the initial step toward generating the foundation document, the controversy over measurement methods must be met head on and resolved. Only then can the recommended practice for measurement be established—which is a prerequisite for progression to search unit performance standardization.

In the opinion of the author, the technology is available to formulate an initial, meaningful document so desperately needed. Some control is better than no control at all; a limited document is better than no document at all. A sophisticated and all encompassing document will follow as a national process of evolution.

The task is not small; it will require concentration of effort, continuity, and the support of industry and governmental agencies. The effort in the past has suffered from a lack of this support; the need today demands that such support be given.

W. F. Hartman[1]

Towards Standards for Acoustic Emission Technology

REFERENCE: Hartman, W. F., "**Towards Standards for Acoustic Emission Technology,**" *Nondestructive Testing Standards—A Review, ASTM STP 624,* Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 138–145.

ABSTRACT: Five years ago, acoustic emission monitoring was recognized barely as an emerging nondestructive testing (NDT) method; yet significant progress has been made with respect to the establishment of standards. The NDT experts in acoustic emission technology presently are developing standard terminology, standard measurement procedures, standard calibration techniques, and standard personnel qualifications. The major collective efforts are being coordinated by the American Society for Testing and Materials (ASTM), American Society of Mechanical Engineers (ASME), American Society for Nondestructive Testing (ASNT), and the National Bureau of Standards (NBS). In this paper we review the current status of the developing standards, and we discuss some idealized standards that have not been formulated popularly or even seriously proposed. We also show how some of the limitations and deficiencies of the present state of the art can be removed by the evolving or proposed standards.

KEY WORDS: acoustics, emission, nondestructive tests, standards, performance, calibration, frequencies, pressure vessels, hydrostatic tests

The technology of acoustic emission is relatively young, and, therefore, progress towards the creation of its standards is followed easily. Under development are standard terminology, standard measurement procedures, standard calibration techniques, and standard personnel qualifications. The major collective efforts are being coordinated by the American Society for Testing and Materials (ASTM), the American Society of Mechanical Engineers (ASME), the American Society for Nondestructive Testing (ASNT) and the National Bureau of Standards (NBS). Here we trace the achievements leading to the current status of the standards and we propose guidelines for future development of standards.

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Acoustic Emission Terminology

Although the monitoring of acoustic emission (AE) as a nondestructive testing (NDT) technique had its United States origins in the early 1960s, its formal recognition as an emerging technology has been more recent. Since its establishment requires authoritative consensus, standards for an emerging technology usually stem from a recognized collegiality of experts. So it has been for AE technology. In 1967 there was founded the Acoustic Emission Working Group (AEWG), an independent forum created for the regular exchange of technical information and the adoption of uniform technology.

In 1971 the AEWG released a subcommittee report on "Recommended AE Terminology," thus "...promoting the *standard* usage of these terms within the technical community."[2] That report was included in an ASTM special technical publication on acoustic emission which contained the papers of the first ASTM sponsored symposium on AE.[3] The recommended terminology in 1971 has served primarily as a standard debating topic, not only within AEWG but, since 1972, within the AE terminology section of the ASTM Subcommittee E07.04 on Acoustic Emission. After much discussion and many revisions, that subcommittee is very near to completing an "acoustic emission glossary."

One of the first things that should emerge from a standard forum is standard terminology. The AE glossary, as proposed by ASTM, contains definitions of the following: acoustic emission, burst emission, continuous emission, AE event, AE signal, AE count, AE count rate, event count, cumulative event count, event count rate, AE signature, arrival time interval, Kaiser effect, AE event energy, AE energy, AE energy release rate, cumulative AE amplitude distribution, cumulative event amplitude distribution, differential amplitude distribution, differential event amplitude distribution, AE signal power, AE signal energy, source activity, stimulation, active source, critically active source, and intensity. It seems appropriate that here we should give the proposed definition of acoustic emission (AE)—"A transient elastic wave generated by the rapid release of energy from a localized source within a material."

It is anticipated that, when it is accepted by ASTM, the proposed AE glossary will be used by many national societies, including ASNT, ASME, and the American Society for Metals (ASM) all of whom are preparing various documents on AE.

Performance Criteria for AE Instrumentation

It is important to note that none of these topics pertain to a specific type

[2]Spanner, J. C., *Acoustic Emission Techniques and Applications,* Intex Publishing Co., Evanston, Ill., 1974.

[3]*Acoustic Emission, ASTM STP 505,* American Society for Testing and Materials, 1972.

of instrumentation. Although the many defined characteristics of AE are measured throughout the world using similar instruments, there should never be a trend towards standardization of AE instrumentation. The variety of measurement techniques, the creation of new techniques, and the evolving capabilities of measuring new things are essential in order to maintain the vigorous growth and progress of this technology. On the other hand, minimum performance criteria should be established for those measurement tasks which are traditionally common to AE instrumentation.

Prior to checking the performance of AE instrumentation, it is necessary to install AE sensor(s). Therefore, it is important that there be a recommended practice for mounting AE sensors. A section of ASTM Subcommittee E07.04 has prepared a draft on this topic. This document defines popular mounting techniques, provides a guideline for the selection of mounting fixtures, and discusses several simple, important precautions that many of the present-day experts learned through mistakes. One additional contribution to this area could be the development of standard forms of describing the pertinent physical and chemical properties of acoustic couplant materials.

ASTM Subcommittee E07.04 has an AE instrumentation section, which is in the process of revising two preliminary documents: "Recommended Practice For Assuring The Performance of a Single Channel Acoustic Emission Counting System," and "Recommended Practice for the Calibration of an Acoustic Emission System Required For Detection and Location Analysis." The first of these hopefully will make it possible for two AE workers, who are conducting the identical experiment with the same sensor, to obtain nearly the same results, even though they may be using different instrumentation. This means that the most classical type of AE measurement can be performed equivalently by dissimilar instrumentation systems, and the results will be quantitatively consistent. This seemingly trivial task requires the popular adoption of a standard procedure. The second document is very important as it directly relates to the most familiar kinds of applications, AE monitoring during testing of pressure vessels and other large structures, such as aircraft, highway structures, marine structures, pipes, etc.

AE Applications

If one application were to be chosen as a standard application, it would be the AE monitoring during hydrotesting of vessels. Eventually to be recognized as a routine application of AE technology, it is one of the fre-

[4]Schofield, B. H. in *Monitoring Structural Integrity by Acoustic Emission, ASTM STP 571,* American Society for Testing and Materials, 1975, pp. 3-10.

quently publicized uses of AE. At the ASTM symposium on monitoring structural integrity by acoustic emission, held in 1974, Schofield maintained that, "In the area of pressure vessel integrity the method has no peer in terms of ultimate potential. ... It should be recognized by those in the pressure vessel industry that development of codes and standards is inevitable, in that they will play an influential role within this industry."[4] Since then, two procedural guides have been prepared: the ASME Proposed Standard for Acoustic Emission Examination During Application of Pressure (E00096) and ASTM Recommended Practice for Acoustic Emission Monitoring of Structures During Controlled Stimulation (E 596-76). These guidelines are similar, each containing recommendations for calibration, test procedure, records, interpretation of results, and personnel qualification.

One of the more important guidelines is the interpretation of results. ASTM Recommended Practice E 596-76 suggests that AE sources be classified with respect to their acoustic activity and intensity:

> A source's acoustic activity is normally measured by event count or emission count. A source is considered to be *active* if its event count or emission count continues to increase with increasing or constant stimulation. A source is considered to be *critically active* if the derivative of its event count, or emission count, with respect to the stimulus, continuously increases with increasing stimulation, or with time under constant stimulus. (see Fig. 1)
>
> An intensity measure of a source is its average amplitude per event. Also, the emission count per event, the emission energy per event, or other quantities that can be shown to be related to the amplitude of the signal, can be used as intensity measures. A source is considered to be *intense* if it is active and its intensity measure consistently exceeds, by a specified amount, the average intensity of active sources. The intensity of a source can be calculated for increments of the stimulus or of events. An intense source is considered to be

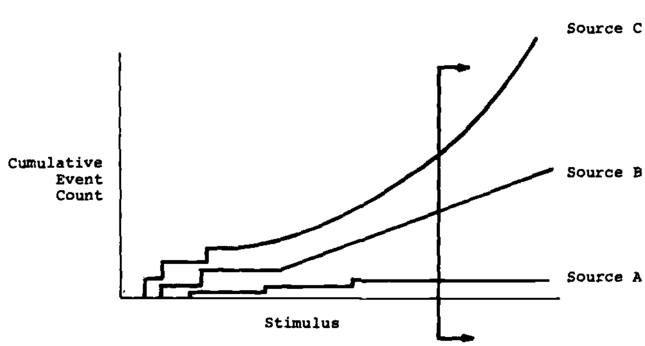

FIG. 1—*Schematic representation of three different source types. To the right of the vertical line, A is inactive, B is active, and C is critically active.*

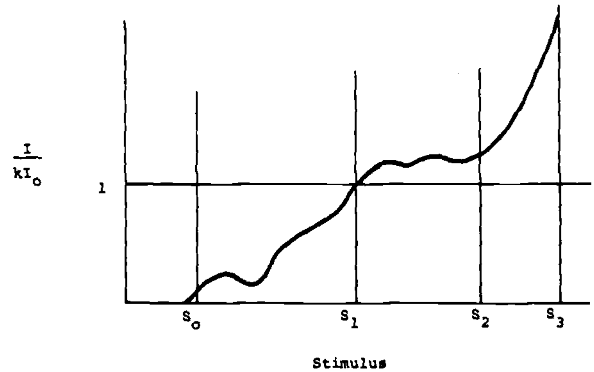

FIG. 2—*Source intensity,* I, *divided by a weighted average intensity of all sources,* kI_0, *plotted against the stimulus,* S. *Four different regions are shown: prior to* S_0, *the source was inactive; between* S_0 *and* S_1, *the source was of low intensity; between* S_1 *and* S_2, *the source is classified as intense; between* S_2 *and* S_3, *the source is classified as critically intense.*

critically intense if its intensity continuously increases with increasing stimulation, or with time under constant stimulus. (see Fig. 2)

In addition to activity and intensity, another characteristic of each detected AE source that should be considered for source classification is the size of the "region" of the located source. The clustering of the located events from a sharp discontinuity, such as a crack, is usually dense, while regions of plastic deformation associated with, say, corrosion pits, result in source areas that show more uncertainity in the definition of their size, the events being contained rather sparsely in the region. In most cases, a growing crack is considered to be the more serious defect. However, activity and intensity may not suffice for distinguishing between the two. Normally there is subjective judgement on what size of location bundle constitutes an isolated source. This situation could be improved by the formulation of some standard guidelines for measuring the "confines" of the source.

The preparation of both the ASME proposed standard and the ASTM recommended practice was influenced substantially by the application of preservice and in-service inspection of nuclear reactor vessels and components. Nevertheless, the makers of both documents attempted to produce a general reference. As a result, each document displays an obvious lack of sensitivity to the AE properties of different materials.

If a general procedure is to work, especially with respect to interpretation of results, then it should contain an accommodation for the specific known AE characteristics of the material being tested. Otherwise, the classification of AE sources, by absolute standards, certainly will be misleading. To illustrate the significance of this, compare the probable AE behavior of geometrically similar vessels, one of stainless steel and the other of high strength steel, during an overpressurization test. Quantitatively, the stainless steel is known to be a weak acoustic emitter for both plastic deformation and crack growth, while the high strength steel is just the opposite. Without some regard, quantitatively, for the different AE characteristics, interpretation of data according to a general guideline could be inadequate. Therefore, one giant vacancy in a list of AE standards is the availability of reference AE characteristics for a variety of materials. Since it is very improbable that this will be done for all materials of interest, then an alternative is a recommended practice or a standard procedure for determining the appropriate AE properties of the materials that comprise each test structure.

The ASME Ad Hoc Working Group on AE is continuing to improve its proposed standard, especially with respect to "calibration procedures" and "interpretation of results." Since recent revisions to the federal regulations for the safety assurance of nuclear power plants require in-service inspection, to the extent feasible, of all nuclear vessels according to Section XI of the *ASME Boiler and Pressure Vessel Code,* there are increased efforts to prepare the standard for acceptance by Section XI. Since AE is the only NDT technique that can be used for many, otherwise inaccessible, regions of some operating reactor vessels, its pending inclusion into the code has taken on new significance.

Calibration

All of the committees and groups, working on the formulation of AE standards, collectively have pursued the development of a calibration reference for AE sensors. That task has now been taken up by NBS. The Electric Power Research Institute and NBS have initiated a jointly sponsored program in AE research. One of the major objectives of that program is to establish reference standards and test methods for calibration of AE detection systems. NBS is developing a test system that uses a large block of metal with two flat parallel faces as a transfer medium for the acoustic signals. On one face of the block a step function of force is applied externally. The directly transmitted sound waves from the event are recorded by a displacement-sensing electrostatic transducer. Studies of both surface waves and bulk waves are planned. Work will be directed towards developing methods to obtain a spectral analysis of the acoustic signatures. Then, application of a known step function of force allows an absolute calibration of any AE receiving transducer, provided that the interactive effects of the transfer block and the transducer's impedance are known. The solution of these problems will enable the adoption of the system as a reference standard for the absolute calibration of ultrasonic receiving transducers. NBS also will determine the means by which the calibration methods can be transferred to the technical community.

Representatives of the NBS AE-sensor calibration program regularly participate in the ASME and ASTM meetings. Therefore, the AE technical community is assured that the work at NBS is both generally responsive to the practical needs and thoroughly interfaced with any parallel efforts.

Other Activities Influencing AE Standards

Generally, it is conceded that traditional measures of AE, such as oscillation and event counting, although the primary means of AE investigation, do not have sufficient capability for resolving differences in features of the stress waves that are generated by dissimilar processes. The variety of mechanically, chemically, and thermally activated AE events can be potentially characterized with respect to their specific source by analyzing and interpreting the information contained in the frequency spectra of these emissions. Recently, there has been increased research activity into the area of frequency analysis of AE signals. The AE program at NBS includes the development of theoretical analysis of AE spectra from moving defects and the correlation of that analysis with experimental observations. Basically, that study will determine as much as possible about the specimen transfer functions in various materials and geometries. It also will determine those spectral characteristics of defect motion which most influences the AE spectrum. For example, attempts will be made to find characteristics which permit the distinction between moving cracks and moving dislocations. The program is obviously an ambitious one; however, it does involve, on the experimental side, materials commonly used in nuclear reactors and pressure vessels. Cracks will be propagated under conditions of fatigue loading as well as chemical and electrochemical corrosion. It is anticipated that crack velocities can be correlated with frequency spectrum of the AE signals. It is obvious that there will be widespread interest in this program as it progresses.

The AEWG also is coordinating a study of frequency analysis of AE signals. Approximately 18 AE experts are participating in this program, which involves analysis of AE signals from stress corrosion cracking, plastic deformation of steel, and deformation and fracture of a graphite-epoxy composite material.

As the programs in frequency analysis progress, it could become appropriate to formulate consensus standards for both procedure and interpretation of frequency content of AE signals.

Other activities, which certainly will influence the development of standards, include: work by the ASNT AE Committee on the creation of a supplement of AE for the NDT personnel qualification documents, the publishing of an AE volume of the ASNT *NDT Handbook,* and the incorporation of AE NDT methods into a forthcoming volume of the ASM *Metals Handbook* on NDT.

Conclusions

NDT Standards for AE technology are evolving. Official documents on terminology, acceptance criteria, test procedures, calibration, and personnel qualification are being prepared by ASTM, ASME, NBS, and ASNT. Although the NDT applications of AE are various and numerous, AE monitoring during hydrotesting of pressure vessels remains as the primary interest of most of the technical participants in the development of standards.

C. E. Burley[1]

Calibration Blocks for Ultrasonic Testing

REFERENCE: Burley, C. E., "**Calibration Blocks for Ultrasonic Testing,**" *Nondestructive Testing Standards—A Review, ASTM STP 624,* Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 146–158.

ABSTRACT: The historical development of test blocks is reviewed briefly, leading to the development of the most recent ASTM standards. The large number of test blocks developed by other than ASTM sources is outlined, together with the problems presented by this proliferation of standards.

The current status of ASTM Recommended Practice for Fabricating and Checking Aluminum Ultrasonic Standard Reference Blocks (E 127-75) and ASTM Recommended Practice for Fabrication and Control of Steel Reference Blocks Used in Ultrasonic Inspection (E 428-71(1975)) for flat entry surface standards is discussed, together with the requirements to apply and duplicate the specified calibration procedures.

Current activities of ASTM to improve existing standards are outlined. In conclusion, some requirements for the development of new standards are advanced.

KEY WORDS: nondestructive testing, ultrasonic tests, calibration, test blocks, standards, aluminum, steels

Nondestructive inspection (NDI), like other quality control processes, is a method by which we compare the unknown with the known. The "known" we generally refer to as "standards" or "calibration sources." Ultrasonic technologists have long recognized the need for standards, since the indication of our test results—generally a "blip" on the face of a cathode ray tube—may or may not bear any resemblance to the source of the blip. In radiography and penetrant testing, the unknown is physically capable of measurement by observation of the radiographic film or developed penetrant. But in ultrasonics, we have only an electrical signal, after several stages of electronic amplification and rectification, to indicate that an acoustic mismatch—the physical source of all ultrasonic inspection data—has been detected.

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Although early ultrasonic tests, *circa* 1940s, primarily were qualitative and required calibration only to ensure reproducibility, the trend toward using ultrasonic testing as a more quantitative inspection soon developed. When inspection required specific techniques and established the acceptance or rejection of a part, the standardization of ultrasonic tests to reliable reference standards became essential.

Thus, in 1951, ASTM Subcommittee E07.06 on Ultrasonic Testing Procedure of Committee E-7 on Nondestructive Testing undertook the development of practical reference standards. This work, which led in 1958 to the publishing of ASTM Recommended Practice for Fabricating and Checking Aluminum Alloy Standard Reference Blocks (E 127)—as well as a description of the large number of early reference blocks developed by Sperry, Grumann, Curtis-Wright, Alcoa, Hitt and others, is well documented in the paper of Panian and Van Valkenburg [*1*].[2] The ASTM Recommended Practice E 127 blocks contain flat bottom hole reflectors which are calibrated for ultrasonic response using external references.

ASTM Recommended Practice E 127 was revised in 1961 and 1964, and calibration test blocks fabricated to this practice are in widespread use. As ultrasonic technology advanced, it became apparent in the late 1960s that the procedures for checking the ultrasonic response of these blocks were no longer appropriate or even capable of being accomplished. A thorough revision of the checking procedures was undertaken by ASTM Subcommittee E07.06 Section 2, and a new version, E 127-75, is now effective. This document will be discussed in a subsequent section.

The influence of ASTM Recommended Practice E 127, although restricted in its scope to aluminum, has been felt in industrial standards for all materials.

In 1953, an ASTM task force was formed to prepare a specification which would cover steel reference blocks. For a period, the work of this committee was directed to applying ASTM Recommended Practice E 127 principles to steel. Since ultrasonic response is not only dependent upon the physical characteristics of the acoustic targets but is associated significantly with the attenuation properties of the test block material, standardization of the physical target characteristics in the presence of the undetermined material variables was difficult and progress was very limited. In 1968, this task group was reorganized and, in 1971, ASTM Recommended Practice for Fabrication and Control of Steel Reference Blocks Used in Ultrasonic Inspection (E 428) was adopted.

The development and philosophy of this document are included in the paper by Ronca [*2*]. Suffice it to say here that ASTM Recommended Practice E 428, in contrast to E 127, does not utilize external references for standardization purposes. Instead, the fabrication procedures for

[2]The italic numbers in brackets refer to the list of references appended to this paper.

blocks are standardized as carefully as possible and rigid examination of the machined flat bottom hole (FBH) targets is required rather than standardizing the ultrasonic response using external references.

Both of these documents utilize reference blocks with flat entry surfaces. ASTM task groups have considered the desirability of establishing test blocks with convex and concave entry surfaces, but no documents have been formalized yet.

Many other reference blocks have been fabricated for specific products, for example, welded plate and pipe, extruded tube and rod, forgings, castings, etc., by various users and trade associations. ASTM recommended practices, such as ASTM Recommended Practice for Ultrasonic Contact Examination of Weldments (E 164-74) and ASTM Ultrasonic Inspection of Longitudinal and Spiral Welds of Welded Pipe and Tubing (E 273-68(1974)), specify reference standards or test blocks different from the FBH blocks that have been referenced.

To conclude this brief introduction, it is probably fair to say that ultrasonic test or calibration blocks have not yet reached the degree of precision desired by ultrasonic technologists. Consider the following quotation from Roberts [*3*]

> Despite the advances that have been made, nondestructive evaluation (NDE) is not yet a precise technique. Consider ultrasonic testing, one of the most popular NDE approaches. No standard is available against which to make meaningful calibrations; phase and frequency data that could greatly increase the information output are ignored; and automation to increase efficiency and reduce operator variability needs to be more widely used ..... A great deal of fundamental work lies ahead if NDE is to become a truly useful, quantitative tool.

While I am not in full agreement with Roberts' assessment of our current stage of standards development, his conclusions are certainly pertinent to the theme of this symposium.

Uses and Types of Calibration Standards

Ultrasonic inspection procedures are based on the use of test blocks manufactured from carefully selected materials in which calibrated discontinuities have been machined. While attempts have been made to quantify flat reflector systems without actually using test blocks [*4,5*], this paper will not attempt to assess either the values or the limitations of such methods.

Reference blocks by definition from ASTM Definition of Terms Relating to Ultrasonic Testing (E 500-74) are blocks used to establish a measurement scale and are means of producing reflections of known characteristics. There are at least five reasons for the use of such reference standards, for example to establish inspection procedures, determine inspection sensitivity level, check equipment performance, prove the acceptability of components or materials, and permit repeatability of inspection. All of these are of equal importance to NDI and should be used as a basis for evaluating test blocks.

There is no one type of ultrasonic reference standard that is suitable in all ultrasonic applications and inspection procedures. An excellent summary and description of many of the test blocks in use has been given by Ellerington [6]. Reference standards commercially available today [7] include most of the following:

1. ASTM type reference blocks (flat surface)
   a. Area-amplitude set
   b. Distance-amplitude set
2. Resolution blocks
3. Thickness standards (step and taper gages)
4. Angle-beam blocks (in particular, the International Institute of Welding (IIW) block)
5. Convex and concave surface blocks
6. Pipe and tubing standards (with V-, buttress-, or U-shaped notches)
7. Delta reference blocks
8. Bureau of Public Roads/American Welding Society (AWS) reference blocks (for structural welds)
9. Cylindrical reference blocks
10. Custom or special reference blocks (standards manufactured by many companies from an actual part similar in all respects to those being inspected)

From this list, it should be obvious that there is great proliferation of standards. In fact, it is not unusual to see cabinets full of test blocks of various configurations, sizes, and alloys. Whether or not this is good depends upon your position. For a supplier of ultrasonically inspected material, it requires a multiplicity of test methods and calibrations and increases the cost of inspection. For the designer or product quality control user, each item is inspected to his specific requirements. However, the results of any one user may not be comparable with the results of other users.

There appears to be no simple solution to this proliferation of standards. Improved technology may and should reduce the number of test blocks required. Hopefully, a universal reference system will be adopted. It is very important that all persons responsible for establishing and using ultrasonic inspection procedures and specifications be fully aware of the advantages and limitations of the available standards. The validity of any test, as well as the qualitative and quantitative interpretation of test data, is strongly influenced, if not completely determined, by the standards used.

Current Status of ASTM Test Blocks

Since time will not permit an analysis of all the test blocks that have been listed, the balance of this presentation is devoted primarily to discussion of the most widely used test blocks—the ASTM series.

The ASTM Recommended Practice E 127 blocks are all based on the amplitude response of FBHs drilled into 7075 aluminum alloy rod. Figure 1 shows a typical ASTM reference block. Each block is identified by the diameter of the FBH reflector and the metal distance from the front or entry surface of the block to the top of the FBH, for example, a 3-0175 designation indicates a 3/64-in.-diameter FBH which is 1¾ in. below the entry surface of the test block.

While any precisely drilled holes in test blocks can serve to (*a*) establish test procedures, (*b*) set sensitivity level, (*c*) check equipment performance, and (*d*) permit test repeatability at *any one* inspection site, using another set of holes in another set of blocks at another location necessarily will not be the same test. Thus, originally, the amplitude of ultrasonic response from each test block was measured against the amplitude of response from known reflectors, in this case, spherical steel balls. While no claim was made that such a reflection amplitude calibration would give the actual physical dimensions of natural reflectors, it was strongly felt, by the aluminum producers in particular, that an industry-wide ultrasonic inspection standard, with specific ultrasonic discontinuity limits [*8*], would be meaningless if each inspection site tested to different sensitivity levels. Unfortunately, during the 1960s, the calibration procedures outlined in ASTM Recommended Practice E 127-64 became impossible to duplicate. Not only had the metallurgical characteristics of 7075 rod changed, but search units and electronics had changed. Vendors could certify that their test blocks met the dimensional requirements of ASTM Recommended Practice E 127-64 but could not certify their ultrasonic response to this recommended practice.

Starting in 1972, a task group from ASTM Subcommittee E07.06, Section 2, Aluminum Reference Standards, tried several approaches to resolve the problems inherent in such a calibration and finally came up with a revision which has now received society acceptance as ASTM Recom-

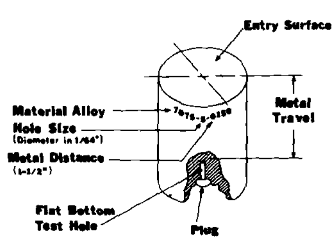

FIG. 1—*Typical ASTM reference block.*

mended Practice E 127-75. In addition to developing a procedure that was reproducible, the task group felt it desirable at this time to have a procedure that would not obsolete all existing ASTM test blocks.

The fabrication, dimensions, and block designations introduced in 1958 have been retained. For block material, aluminum alloy 7075-T6 has been retained, and extruded rod has been included, as well as rolled rod. (Extruded rod is available now more readily than rolled rod.) In addition, a normalization treatment has been included as a metallurgical option. Unfortunately, this heat treatment cannot be used on existing blocks which do not meet the current specifications unless the plug is removed, the FBH cleaned, and the block replugged.

The ultrasonic response of distance-amplitude blocks meeting ASTM Recommended Practice E 127-75 must match the curves shown in Fig. 2

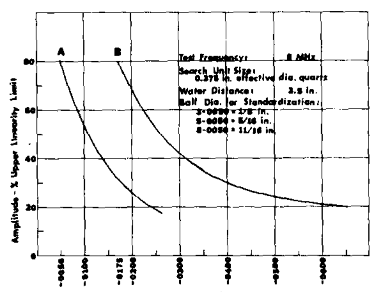

FIG. 2—*Distance-amplitude response curves (A and B) showing the interrelationship between ultrasonic standard reference blocks of various lengths and containing FBH (from ASTM Recommended Practice E 127-75).*

within ±2 dB. For each diameter FBH, only one steel reference ball is required, instead of a different ball for each block. The gain of the measuring system is adjusted so that the response from each reference ball initially is equal to 80 percent of the system upper linearity limit. Starting with a metal distance of 0.5 in., Curve A data points are obtained for each FBH. At amplitudes less than 20 percent, the ability to read typical oscilloscope displays accurately is very limited. Thus, the system gain is increased approximately 8 dB to give Curve B data points. (The details of this procedure are fully explained in ASTM Recommended Practice E 127-75.)

Ultrasonic response must be obtained using a specific search unit (5-MHz quartz, 3/8-in. effective diameter) and a tuned pulser/receiver. The axial distance-amplitude characteristics and the beam characteristics at the Y_0^+ and Y_1^- points of acceptable search units are specified. Following these requirements, each member of the task group was able to duplicate the response curves on specific test blocks. Several sets of blocks have now been fabricated and certified to meet this specification.

Area-amplitude blocks also are tied into this calibration, at the option of the purchaser. Basically, the area-amplitude set must match the curve shown in Fig. 3; if the response of an area-amplitude set is desired to be the same as that of the same blocks in a distance-amplitude set, each block must also agree with Fig. 2. Since, in many cases, area-amplitude blocks are used to determine instrument linearity or to adjust a distance-amplitude curve for a larger or smaller set of FBHs, and *not* as an amplitude calibration, ASTM Recommended Practice E 127-75 provides this option.

All users and purchasers of test blocks desiring their sets to meet ASTM Recommended Practice E 127-75 ultrasonic response levels should require curves, such as Figs. 2 and 3, from the block vendor. Blocks showing response referenced to ASTM Recommended Practice E 127-64 will not necessarily meet the requirements of ASTM Recommended Practice E 127-75!

While these improvements in ASTM Recommended Practice E 127-75 make it possible to produce test blocks meeting ASTM requirements, our task group is not satisfied with all control parameters. We are actively pursuing, with the cooperation of the National Bureau of Standards (NBS), means to define standard reference blocks better. For example, the material specifications should include an improved method of measuring ultrasonic response of the raw material—7075-T6 rod.

A second parameter of concern is the need to use quartz search units and a tuned pulser. To date, no other search unit/pulser combination has been shown to give reproducible data. Certainly no one can deny the fact that beam profiles and frequency spectra have considerable effect on response amplitude. This is encountered as different users use different electronic systems and search units to perform ultrasonic inspection. A distance-amplitude curve obtained with a ceramic 10-MHz search unit with a broadband amplifier will not match the distance-amplitude

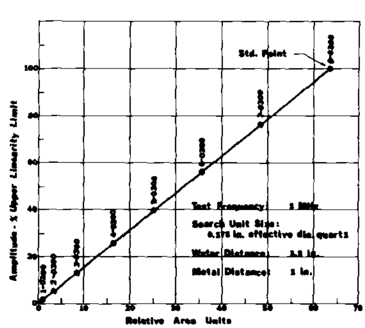

FIG. 3—*Area-amplitude response curve showing interrelationship between ultrasonic standard reference blocks containing holes of various sizes at constant metal distances* (*from ASTM Recommended Practice E 127-75*).

curve shown in ASTM Recommended Practice E 127-75. Thus, spectrum analysis methods are being investigated for control.

Also, in order to obtain adequate reproducibility, a tolerance band of ±2 dB in amplitude of response is required. We would like to reduce this spread to no greater than ±1 dB. When standardization of search units, electronic pulsers, and receivers has been accomplished, an improved method of test block standardization should be possible.

In contrast to the approach taken in ASTM Recommended Practice E 127, the ASTM document for steel reference blocks (ASTM Recommended Practice E 428) does *not* require ultrasonic standardization with external references. Since the document for steel covers blocks made of steels with a wide range of attenuation properties, the emphasis in ASTM Recommended Practice E 428 is on standardization of fabrication procedures and measurement of flat bottom hole configuration—squareness, flatness, and surface finish—by a plastic replication technique. However, after fabricating and checking, blocks must be evaluated ultrasonically as a set, and any block that exhibits erratic ultrasonic response and does not fall within the apparent normal area-amplitude or distance-amplitude curve does not qualify as an ASTM Recommended Practice E 428 block.

The block identification system used in ASTM Recommended Practice E 127 is also a part of ASTM Recommended Practice E 428 with the addition that the American Iron and Steel Institute (AISI) alloy or grade is used (for example, 4340-5-0300 signifies an AISI 4340 steel reference block with a 5/64-in.-diameter FBH at a 3-in. metal distance).

Since ASTM Recommended Practice E 428 uses no external references, specific attention is paid to the ultrasonic attenuation of the raw material. The material used must display acoustic attenuation similar to the material to be examined. Grain size, grain flow, composition, and surface finish are variables to be considered. The exponential decay of multiple back reflections is used to monitor the attenuation characteristics.

Typical area-amplitude and distance-amplitude response curves from 4340 steel reference blocks are shown in Figs. 4 and 5. The recommended

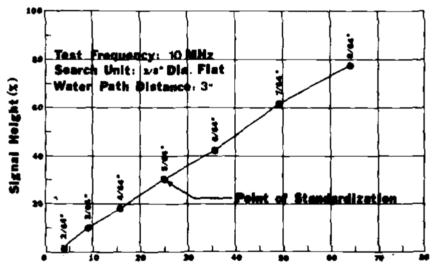

FIG. 4—*Typical area-amplitude response curve from 4340 steel reference blocks (from ASTM Recommended Practice E 428-71 (1975)).*

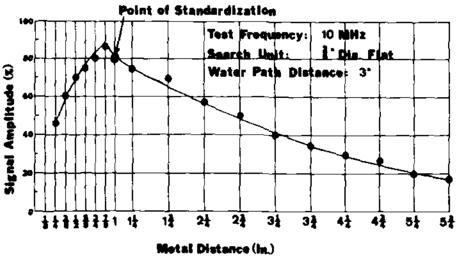

FIG. 5—*Typical distance-amplitude response curve from 4340 steel reference blocks* (*from ASTM Recommended Practice E 428-71* (*1975*)).

practice does not specify test frequency or search unit characteristics. Instead, for any given combination of search unit, coaxial cable and instrument, the ASTM Recommended Practice E 428 blocks are designed to produce a maximum amplitude response.

This discussion has attempted to point up the major strengths and limitations of the existing ASTM documents for test blocks. Certainly few, if any, of us are completely satisfied with our existing standards; however, when they are used with intelligent understanding of the entire testing situation, reliable and reproducible measurements can be made by competent operators.

Other ASTM Test Block Activity

The preceding section has been related primarily to test blocks used in pulse-echo longitudinal inspection of flat surfaces. Of concern to ASTM has been the subject of curved entry surface standards. Section 2 of ASTM Subcommittee E07.06 conducted an interlaboratory test of convex surface aluminum blocks fabricated to Boeing Process Specification on Ultrasonic Inspection (BAC 5439) in an effort to develop a correction table for ASTM Recommended Practice E 127 blocks or a new recommended practice. The results of this interlaboratory test, conducted among twelve users and using three sets of blocks fabricated by different vendors, showed great variation, particularly as metal distance increased over 1½ in., as shown in Table 1. A typical block is shown in Fig. 6. A survey of aerospace companies in 1975 showed little interest or need for an ASTM specification for aluminum curved surface blocks.

In contrast, the steel group is planning to prepare a document or supplement to ASTM Recommended Practice E 428-71 (1975) for curved surfaces. For steel, flat blocks have been used to examine curved entry surfaces by applying correction factors such as found in ASTM Recommended Practice for Ultrasonic Inspection of Heavy Steel Forgings (A 388-75). However, recent studies, according to Ronca [2], indicate that

TABLE 1—*Range of comparative amplitudes of response-cylindrical entry surface test blocks, ASTM Section E07.06.02 interlaboratory test, 1972.*

FBH Diameter, in.	Metal Distance, in.	Amplitude Ratio[a]					
		Block A[b]	Block B	Block C	Block D[c]	Block E	Block F
3/64	½	1.9 to 8.0	1.5 to 8.0	2.0 to 10.0	. . .	. . .	. . .
	1	6.5 to 25.0	7.0 to 40.0	6.5 to 40.0	4.0 to 8.0	3.5 to 40.0	3.5 to 8.0
	1½	6.5 to 40.0	6.0 to 40.0	7.5 to 40.0	. . .	. . .	. . .
	2	. . .	. . .	. . .	5.0 to 20.0	5.5 to 40.0	6.0 to 40.0
	3	. . .	. . .	. . .	8.0 to 40.0	8.0 to 40.0	10.5 to 40.0
5/64	½	2.4 to 40.0	2.0 to 16.0	2.0 to 16.0	. . .	. . .	. . .
	1	6.5 to 16.5	5.5 to 40.0	5.5 to 40.0	3.5 to 5.0	2.5 to 5.5	3.5 to 5.5
	1½	9.0 to 25.0	6.5 to 40.0	7.0 to 40.0	. . .	. . .	. . .
	2	. . .	. . .	. . .	4.0 to 16.0	4.0 to 16.0	4.5 to 16.0
	3	. . .	. . .	. . .	6.5 to 40.0	6.5 to 40.0	8.0 to 40.0
8/64	½	2.0 to 40.0	2.0 to 40.0	2.0 to 40.0	. . .	. . .	. . .
	1	5.5 to 10.0	5.5 to 40.0	5.0 to 40.0	2.5 to 5.0	2.5 to 4.5	2.5 to 6.0
	1½	10.0 to 40.0	7.5 to 40.0	8.0 to 40.0	. . .	. . .	. . .
	2	. . .	. . .	. . .	3.0 to 12.0	3.0 to 12.0	3.5 to 16.0
	3	. . .	. . .	. . .	10.0 to 40.0	10.0 to 40.0	12.0 to 40.0

[a] All numbers in table are ratios of echo amplitude from a flat block to that from a curved block, both having same FBH and metal distance.
[b] Blocks A, B, and C—2-in.-diameter rounds (per Fig. 6).
[c] Blocks D, E, and F—4-in.-diameter rounds (per Fig. 6).

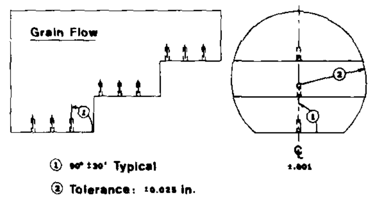

FIG. 6—*Convex surface reference block configuration per Boeing BAC 5439.*

coupling efficiencies are more sensitive to the beam profiles of search units used than had been recognized previously.

Angle beam test blocks also have been considered by the aluminum section. A task group currently is charged with conducting an interlaboratory test on blocks fabricated by three aluminum producers according to McDonnell-Douglas Process Specification on Ultrasonic Inspection (P.S. 21211). A diagram of this type of test block is given in Fig. 7.

As of this date, then, there are no ASTM practices for the fabrication and checking of other than flat surface ultrasonic test blocks.

Future of Test Blocks

While test blocks may not be the ideal method of standardizing ultrasonic inspection, no other standardization method has received wide acceptance in the United States.

A major problem with use of test blocks is the lack of a universally accepted set of reference blocks. ASTM Recommended Practice E 127-75 has tried to overcome this problem by including external references—steel balls. Undoubtedly, the creation of one or more sets of master blocks, under the control of a recognized standards laboratory, such as NBS, could alleviate this problem. I am sure other authors will elaborate on this topic. There is a lot of work that needs to be done, and joint industry-government support should not only speed up progress, but also permit expansion of activities. However, there should be adequate liaison to minimize duplication of effort. At present, there are no standards for ultrasonic calibration blocks traceable to NBS.

A major effort should be devoted to obtaining a better understanding of the interaction of materials, seach units, and electronic intrumentation on ultrasonic response. The work of Baborovsky et al [9] in studying the interaction of the acoustic pulse with a defect is one example. Both Schlieren photography and computer simulations were used. To obtain consistent experimental data, they found it necessary to develop special procedures to eliminate the effects of constructional artifacts on the response of artificial defects.

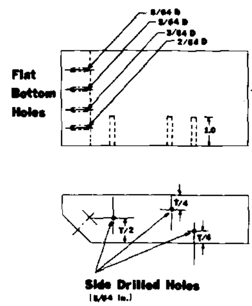

FIG. 7—*Flat surface angle-beam configuration per McDonnell-Douglas P.S. 21211.*

Perhaps amplitude of response should be supplemented or even replaced by frequency and phase analysis. Certainly, we require better control of ultrasonic frequency spectra and test instrument characteristics, along with better control of material properties, if we continue along the paths we have followed for some 30 years.

Alternate methods of characterizing ultrasonic information should be encouraged. One example of recent effort is the work of Mucciardi et al [*10*] in applying nonlinear signal processing techniques to ultrasonic waveforms to determine the parameters containing information relative to FBH size discrimination. Waveform data from two different sets of ASTM Recommended Practice E 127 type area-amplitude blocks were obtained using three different search units. Fifteen parameters were found to contain size related information. "Maximum amplitude of the pulse-echo waveform was *not* found to be a discriminating parameter when the transducer and/or transmission medium was changed" [*10*]. These results support the conclusions of our ASTM task group that you cannot reproduce amplitude response curves on a given set of test blocks at different laboratories unless you use the same or equivalent search units and electronic instrumentation.

Acknowledgments

The author acknowledges the assistance and support of members of ASTM Subcommittee E07.06 and, in particular, the members of the task groups responsible for ASTM Recommended Practices E 127-75 and E 428-71 (1975). In preparing this paper, the following made helpful suggestions and contributions: T. F. Drumwright, Alcoa; J. Posakony, Battelle-Northwest; G. F. Ronca, Westinghouse Electric; H. E. Van Valkenburg, Automation Industries; and A. E. Wehrmeister, Babcock and Wilcox.

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J. S. Borucki[1]

An Overview of Magnetic Particle and Liquid Penetrant Methods Documents and Associated Quantitative Measurement Standards Needs

REFERENCE: Borucki, J. S., "**An Overview of Magnetic Particle and Liquid Penetrant Methods Documents and Associated Quantitative Measurement Standards Needs,**" *Nondestructive Testing Standards—A Review, ASTM STP 624,* Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 159–171.

ABSTRACT: The magnetic particle and liquid penetrant inspection methods are the most widely used nondestructive testing methods in industry today, as evidenced by the existence of a multitude of worldwide governmental, institutional, and industrial specifications which govern the use of these processes. However, there are some problem areas, that is, inconsistencies, overlaps, omissions, etc., associated with the various documents which control these two recognized test methods.

Of fundamental importance, and in keeping with the theme of this symposium, this presentation will concentrate on the need for and the problems associated with the development of magnetic particle and liquid penetrant physical property standards and physical performance standards. We recognize the need for reproducible, quantitative, physical, and performance measurement standards such as calibrated cracks, artificial defects, magnetic penetrameters, flux density, "black light," fluorescent brightness, and penetrant removability.

Industry can benefit from the development of such standards. It is our intention, therefore, to discuss this area candidly and seek ways and means of achievement.

KEY WORDS: nondestructive testing, standards, magnetic particle tests, penetrants

Magnetic particle (MPI) and liquid penetrant inspection (LPI) methods of nondestructive testing are used extensively today in virtually all major industries worldwide. Historically, these methods were established in the 1930s and early 1940s.

Through the years, many technological advancements have been achieved

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in penetrant and magnetic particle materials, equipment, and method technology. Today, industry has available a wide variety of LPI and MPI equipment and materials, including both fluorescent and visible dye penetrants, various types of emulsifiers/removers and developers, and both fluorescent and visible magnetic powders. Proper selection among these materials provides varying sensitivities as required. In addition, the processing equipment that exists today runs the gamut from simple devices, such as electromagnetic yokes, prods, and aerosol containers of penetrants and magnetic particles for localized inspection, to more sophisticated equipment for applications, ranging from the inspection of nuts and bolts to jumbo jet landing gear to multiton steel billets.

Inherent in the growth and wide use of the magnetic particle and liquid penetrant methods is in the requirement to control the process and provide consistent inspection reliability. The mere fact that these basic nondestructive testing (NDT) methods have been in use for many years is no assurance that they are being utilized to their fullest capacity. As a matter of fact, there are many instances, which I am certain you can cite, where little or no control is exerted over incoming processing materials, processing cycles, equipment calibration, and personnel qualification. Fortunately, the majority of the worldwide MPI and LPI practices are adequately controlled through various materials and process/method specifications which exist today. Improvements, however, in certain areas of several existing documents is necessary if we are to improve overall inspection reliability. It is the purpose of this session and of our panel experts, therefore, to review and cite specific problem areas and suggest areas for improvement.

Specification Syndrome

In the course of discussion, we will be referring to several of the various magnetic particle and liquid penetrant specifications listed in Appendixes I and II. This list of documents, although extensive, can be simplified by categorizing into industrial, institutional, and governmental material procurement specifications and process control specifications. The material procurement documents, in general, define chemical and physical property requirements and performance criteria and are intended to assure the consistency and uniformity of incoming penetrant and magnetic particle materials. The process control specifications define the process parameters and associated process tolerances for a particular application. In either case, these documents are intended to be specific to the needs of a particular industry and inspection requirements therein.

Some of the basic problems that both the specification writer and the user face in this myriad of specifications are: (*a*) specification differences in the chemical/physical property requirements for various documents, (*b*) specification differences in performance property requirements of various documents, and (*c*) specification differences in processing procedures of various documents. This specification syndrome will be expanded on in more specific detail later in this session.

Before we proceed further, I would like to clarify any misconception that may exist in our understanding of the terms standard and specification. Webster's dictionary defines a "specification" as a detailed, precise presentation; a written description of something. A "standard" is defined as something set up and established by authority as a rule for the measure of quantity, weight, extent, value, or quality. Actually, the documents listed in Appendixes I and II should be classified appropriately as specifications, codes, and procedures, and as can be noted, several have been titled standards.

MPI and LPI Standards Development

The proliferation of MPI and LPI documents which has occurred over the years reflects the technological changes and product and process advancements. Today, industry has at its disposal over 1000 different MPI and LPI products (materials and equipment) with which to carry out their respective inspection requirements.

Obviously, proper control must be exerted over the materials selected for use, and the inspection procedures employed, if a reliable inspection is to be achieved. To this end, specification development bodies continue their never ending battle of updating existing documents and developing new ones as required.

I would like to comment briefly in regard to those individuals who are quick to criticize but slow to assist in our standards development efforts. Documents are generated by individuals, and by individual organizations, and are only as good as the people who write them. When properly executed, all interest areas and viewpoints are represented. When properly coordinated between the various specification writing bodies, overlaps, duplications, contradictions, etc., are minimized greatly.

Ideally, all standards development efforts should be based on fact and avoid causing new problems.

Our primary objective, therefore, is to seek the best possible technical solution for the various technical specification problems which confront us.

Problem Areas and Needs

To assume that all is well in magnetic particle and liquid penetrant documents, to say the least, would be foolhardy. We do have our specification problems, as does everyone else.

Obviously, time will not permit us to cover the advantages, limitations, and anomalies of all of the various documents cited in Appendixes I and II. In the course of this paper, however, we will be discussing several of the more influential documents reflecting specific industry needs.

Although the MPI and LPI user faces the traditional problem of specification conflict, overlaps, etc., the most important problem area of MPI and LPI is the lack of quantitative measurement standards. The need for quantitative measurement standards for performance, reproducibility, and traceability is obvious.

In the liquid penetrant method, we have needed for several years a quantitative method of measuring and rating penetrant system sensitivity. For the past 18 years, industry has adapted either by contractual specification requirement, or by attrition, the doctrines of MIL-I-25135.

MIL-I-25135 is a very influential penetrant materials specification in that the classification and sensitivity rating system defined in this document generally is accepted and referred to on a worldwide basis; its rating and classification, however, has led to a great deal of inconsistency and misinterpretation; it is in dire need of revision.

This penetrant classification system (Table 1) consists of seven groups of penetrant inspection materials, each defined as a family of materials from one source of supply. The original purpose of this classification system was to group the various families of materials by method and type, that is, fluorescent or visible, solvent removable, water washable, or post emulsifiable. Unfortunately, worldwide industry has misinterpreted this classification structure to mean group sensitivity. It is quite common to find that many people are of the opinion that penetrant sensitivity ratings range from Group I (low) to Group VII (ultrahigh), when in fact, Group I defines a visible, solvent removable, family of penetrant materials and Group VII is nothing more than Group VI materials in aerosol containers.

Fundamentally, the penetrant materials classification system of MIL-I-25135 adequately defines and groups penetrant systems into their respective method and type categories. However, it should not be confused with or used to define or rate penetrant sensitivity.

Over the years, there have been several explanations of penetrant sensitivity and of the factors which affect it offered by a number of investigators. None have been able yet to give a clear cut characterization of penetrant sensitivity or provide a definitive sensitivity rating system. What exists is a "rubber ruler" wherein sensitivity classifications are rated generally as normal, high, and ultrahigh, depending on the flaw detection capability of a given penetrant system. There is a general agreement that penetrant sensitivity is the overall flaw detection capability of a given

TABLE 1—*MIL-I-25135 penetrant classification system.*

Group	Penetrant System Description
I	Consisting of a solvent-removable visible dye penetrant, a penetrant remover (solvent), and a dry, wet, or nonaqueous wet developer.
II	Consisting of a postemulsifiable visible dye penetrant, an emulsifier, and a dry, wet, or nonaqueous wet developer.
III	Consisting of a water-washable visible dye penetrant and a dry, wet, or nonaqueous wet developer.
IV	Consisting of a water-washable fluorescent penetrant and a dry, wet, or nonaqueous wet developer.
V	Consisting of a postemulsifiable fluorescent penetrant, an emulsifier, and a dry, wet, or nonaqueous wet developer.
VI	Consisting of a high-sensitivity, postemulsifiable, fluorescent penetrant, an emulsifier, and a dry, wet, or nonaqueous wet developer.
VII	Consisting of an aerosol can of Group VI solvent removable fluorescent penetrant, cleaning remover, and a nonaqueous wet developer.

penetrant system. In effect, it is the ability of the penetrant system to produce a perceptible indication for a given crack dimension and is not limited to one single factor; it is the overall system effectiveness that counts.

Most sensitivity determinations are made visually or electrooptically on various laboratory crack specimens wherein the indication brightness is measured and evaluated. There are several factors, however, which affect the overall sensitivity of a penetrant system, some of which are: fluorescent response of the penetrant at various film thicknesses, choice and concentration of dyes, fluorescent brightness, volatility of penetrant, viscosity of penetrant, heat stability, ultraviolet stability, concentration of emulsifier/remover, type of developer employed, type of emulsifier employed, contamination limits of materials, penetrant application dwell time, emulsification application and contact time, removal procedures, drying procedures (time and temperature), and black light intensity.

For any given penetrant system, its sensitivity or flaw size detection capability will depend on (*a*) the amount of penetrant that gets into the crack, (*b*) the amount of penetrant that remains within the crack after the surface removal step, (*c*) the amount of penetrant that comes back out of the crack during the developing process, (*d*) the visibility of the indication, and (*e*) the "signal to noise ratio" of indication to background interference.

Within the present state of the art, determination of penetrant sensitivity is based on the ability of the penetrant system to indicate various size cracks on various types of artificial defects. The smaller the minimum crack size detected, the more sensitive the penetrant system. For this purpose, several artificial crack devices have been created and utilized over the years. Since so much emphasis is put on these various devices in establishing penetrant sensitivity levels and performance criteria, it is important that their value and limitations be put in proper prospective.

Another area of interest which applies to both MPI and LPI is that of the measurement of fluorescent indication brightness and black light intensity. To date, we have no precise way to standardize the measurement of fluorescent indications or determine the exact level of black light intensity necessary.

The problem associated with the MPI method is similar to LPI in that there is a void in the area of quantitative crack standards for determining system sensitivity. We do have several artificial defect devices such as magnetic penetrameters, scribed ferromagnetic shims, magnetic paste-ons, Ketos rings, and various other devices which are used to varying degrees, but which are only qualitative and not very reproducible.

Specific to MPI is the need to develop a suitable quantitative measurement standard for the determination of the level of flux density within and at the surface of the part. Furthermore, we need to increase our knowledge of and strive further to standardize magnetic particle process techniques to assure proper part magnetization and overall inspection reliability.

A review of existing governmental, industrial, and institutional magnetic particle method documents points up that at present the parameters for magnetic particle inspection are based primarily upon empirical rules which are applicable to parts having a relatively simple geometry and may or may not be applicable to complex structures.

In the "real world" of production magnetic particle inspection, however, part size, geometry, retentivity, and permeability can vary greatly; it is recognized, therefore, that individual magnetizing techniques need to be developed for specific applications. The physical shape of the test part does present an electrical current, and subsequent magnetic field, gradient in such parts which, of course, results in varying field strength within and at the surface of the part. The problem is even more complicated for *in situ* maintenance inspection of installed components and structures.

There is obviously a great deal of investigative work still to be done in the technology of magnetic particle inspection methods, particularly in advancing the traditional empirical "rules of thumb" as related to complex shaped parts. Additional basic studies are also necessary, especially in the relationship between part magnetization and the retentivity and permeability of the particular part alloy.

Additional investigative work is also necessary on the effect of such variables as type of magnetizing current, (that is, alternating current, half-wave direct current, full-wave direct current) as well as current level requirements.

Summary

Fortunately, the majority of the magnetic particle and liquid penetrant practices in use today are controlled relatively through various materials and process specifications. This myriad of documents, however, does need a thorough review and updating with a view toward consolidation and elimination of nonessential documents. Many instances exist where conformance to one document forces noncompliance to another due to differences in process parameters or material specification requirements, or both.

Furthermore, of more fundamental importance is the need to establish reproducible quantitative measurement standards for clarifying and ranking penetrant sensitivity and measuring magnetic flux density.

The elimination of nonessential documents, the consolidation of pertinent documents, and the establishment of reproducible quantitative measurement standards will require the full cooperation and coordination and technical and administrative resources of all of industry and the underlying specification issuing bodies.

APPENDIX I

MPI Method Documents

Issued by[a]	Designation	Date of Issue	Title of Document
USCG	SG-115	3/66	Marine Engineering Regulations and Material Specifications, Subchapter F
USA	MIL-M-11472(2)	11/52	Magnetic Particle Inspection, Process for Ferromagnetic Materials
USA	MIL-M-23527	12/62	Magnetic Particle Inspection Unit, Lightweight
USA	MS-17980A	5/63	Magnetic Particle Indications on Steel Nuts
USN	NAVAIR 00-15PC-503	11/55	Technical Inspection Manual, Volume 3, Section 4, Magnetic Particle Inspection
USN	MIL-STD-288	7/56	Inspection Procedure for Determining the Magnetic Permeability of Wrought Austenite Steel

Issued by[a]	Designation	Date of Issue	Title of Document
USN	NAVSHIPS 0900-006-9010	6/66	Fabrication, Welding and Inspection of HY-80 Submarine Hulls
USN	NAVSHIPS 0900-000-1000	1967	Fabrication, Welding and Inspection of Ship Hulls
USN	NAVSHIPS 250-1500-1 Revision 5	1969	Welding Standard, PWR and Associated Systems
USN	MIL-S-23284	1967	Steel Forgings, Carbon and Alloy, for Shafts, Sleeves, Couplings, and Stock (Rudders and Diving Planes)
AEC (RDT)	F3-6T	1970	Nondestructive Examination, Supplementary Criteria for Use of ASME Section V and USASI B31.7 Division, Reactor Development and Technology
ANSI	B31.7	1969	Code for Pressure Piping, Nuclear Power Piping
ASME	Section VIII and Latest Amendments	1968	Unfired Pressure Vessels
ASME	Section VIII, Division 2 and Latest Amendments	1968	Alternative Rules for Pressure Vessels
ASME	Section V and Latest Amendments		Nuclear Vessels
AAR	M-107	1969	Magnetic Particle Inspection—Wheel Shop Inspection
AWS		1970	Magnetic Particle Inspection
IIW		1969	Magnetic Particle Inspection
IFI	IFI-105	1968	Recommended Practice on Surface Discontinuities on Bolts and Screws for Automotive Applications
SAE	AMS-3040	1974	Magnetic Particle Inspection Material, Dry Method
SAE	AMS-3041	1974	Magnetic Particle Wet Method, Oil Vehicle
SAE	AMS-3042	1974	Magnetic Particle Wet Method, Dry Powder
SAE	AMS-3043	1974	Magnetic Particle Wet Method, Oil Vehicle Aerosol Canned
SAE	AMS-3044	1974	Magnetic Particle, Fluorescent Wet Method, Dry Powder
SAE	AMS-3045	1974	Magnetic Particle, Fluorescent Wet Method, Oil Vehicle
SAE	AMS-3046	1974	Magnetic Particle, Fluorescent Wet Method, Oil Vehicle, Aerosol Canned

Issued by[a]	Designation	Date of Issue	Title of Document
McDonnel-Douglas	PS-21201	1970	Magnetic Particle Inspection
Douglas Aircraft	DPS 4.704		Magnetic Particle Inspection
Rockwell International	ST0501LT0011		Magnetic Particle Inspection
Rolls Royce	T.S.D.#594		Overhaul Process #201—Magnetic Particle Inspection
Boeing	32-21-55 32-13-45		747 Magnetic Particle Examination
General Electric	P3TF9-1		Magnetic Particle Inspection
Pratt & Whitney Aircraft	PMC		Magnetic Particle Inspection
ASTM	A 275-76	1976	Magnetic Particle Examination of Steel Forgings
ASTM	A 340-65(1970)	1965	Definitions of Terms, Symbols, and Conversion Factors Relating to Magnetic Testing
ASTM	A 456-71(1976)	1971	Specification for Magnetic Particle Inspection of Large Crankshaft Forgings
ASTM	E 109-63(1976)	1963	Dry Powder Magnetic Particle Inspection
ASTM	E 125-63(1976)	1963	Reference Photographs for Magnetic Particle Indications on Ferrous Castings
ASTM	E 138-63(1976)	1963	Wet Magnetic Particle Inspection
ASTM	E 269-74	1974	Definitions of Terms Relating to Magnetic Particle Inspection
DOD	MIL-M-11473	1951	Magnetic Particle Inspection, Soundness Requirements for Weldments
DOD	MIL-M-6867C	1969	Magnetic Inspection Units
DOD	MIL-STD-410A	1962	Qualification of Inspection Personnel (Magnetic Particle and Penetrant)
DOD	MIL-STD-271E		Nondestructive Testing Requirements for Metals
DOD	MIL-I-6868 D Amendment 1	1971	Inspection Process, Magnetic Particle
USN	MIL-I-6870B	1965	Inspection Requirements, Nondestructive, for Aircraft Materials and Parts

Issued by[a]	Designation	Date of Issue	Title of Document
USN	NAVSHIPS 250-637-3	1962	Fabrication, Welding, and Inspection of HY-80 Submarine Hulls
USN	NAVSHIPS 0900-003-8000	1967	Surface Inspection Acceptance Standards for Metals
SAE	AMS-2300A	1961	Magnetic Particle Inspection, Premium Aircraft Quality Steel Cleanliness
SAE	AMS-2301D	1967	Magnetic Particle Inspection, Aircraft Quality Steel Cleanliness
SAE	AMS-2640H	1969	Magnetic Particle Inspection
USAF	T.O.33B2-1-1	1963	Inspection of Material, Magnetic Particle Method

[a] AAR — Association of American Railroads
AEC(RDT) — U. S. Atomic Energy Commission, Reactor Development and Technology
ANSI — American National Standards Institute
ASME — American Society of Mechanical Engineers
ASTM — American Society for Testing and Materials
AWS — American Welding Society
DOD — U. S. Department of Defense
IFI — Industrial Fasteners Institute
IIW — International Institute of Welding
SAE — Society of Automotive Engineers
USAF — U. S. Air Force
USCG — U. S. Coast Guard
USA — U. S. Government
USN — U. S. Navy

APPENDIX II

LPI Method Documents

Issued by	Designation	Date of Issue	Title of Document
AEC(RDT)	F3-6T	1974	Nondestructive Evaluation, Supplementary Criteria for Use of ASME Section III and USASI B31.7 Division, Reactor Development and Technology

Issued by	Designation	Date of Issue	Title of Document
ANSI	B31.7	1969	Code for Pressure Piping, Nuclear Power Piping
ASME	Section V and Latest Amendments	1974	Nuclear Vessels
ASME	Section VIII and Latest Amendments	1968	Unfired Pressure Vessels
ASME	Section VIII, Division 2 and Latest Amendments	1968	Alternative Rules for Pressure Vessels
ASME	Section IX and Latest Amendments	1968	Welding Qualifications
ASTM	E 165-75	1975	Recommended Practice for Liquid Penetrant Inspection Method
ASTM	E 270-75	1975	Definitions of Terms Relating to Liquid Penetrant Inspection
USN BuShips	NAVSHIPS 0991-023-3000		Repairs to Bronze Propellers
DOD	MIL-STD-410		Qualification of Inspection Personnel (Magnetic Particle and Penetrant)
DOD	MIL-T-23226B(1)	1969	Tube and Pipe, Corrosion-Resistant, Steel, Seamless
DOD	MIL-I-6866B and Amendment 2	1969	Inspection, Penetrant Method of
DOD	MIL-STD-271E	1973	Nondestructive Testing Requirements for Metals
DOD	MIL-F-38762 and Amendment 1	1968	Fluorescent Penetrant Inspection Units
DOD	MIL-C-6021G	1967	Castings, Classification and Inspection of
DOD	MIL-F-38762 and Amendment 1	1968	Fluorescent Penetrant Inspection Units
DOD	MIL-L-6866B and Amendments 1 and 2	1969	Inspection, Penetrant Method of
USN	MIL-L-6870B	1965	Inspection Requirements, Nondestructive, for Aircraft Materials and Parts
USN	NAVSHIPS 250-637-3	1962	Fabrication, Welding, and Inspection of HY-80 Submarine Hulls
USN	NAVSHIPS 0900-003-8000	1967	Surface Inspection Acceptance Standards for Metals
SAE	AMS 2645F	1969	Fluorescent Penetrant Inspection

Issued by	Designation	Date of Issue	Title of Document
SAE	AMS 2645G	1969	Fluorescent Penetrant Inspection
SAE	AMS 2646B	1964	Contrast Dye Penetrant Inspection
SAE	AMS 3155B	1964	Oil, Fluorescent Penetrant, Water Soluble
SAE	AMS 3156B	1964	Oil, Fluorescent Penetrant, Water Soluble
SAE	AMS 3157A	1964	Oil, Fluorescent Penetrant, High Fluorescence, Solvent Soluble
SAE	AMS 3158	1964	Solution, Fluorescent Penetrant, Water Base
USAF	T.O.42C-1-10	1966	Inspection of Material Fluorescent and Dye Penetrant Methods
USAF	MIL-I-25135C and Amendment 3	1964	Inspection Materials, Penetrant (ASG)
USN	NAVSHIPS 0900-000-1000	1967	Fabrication, Welding, and Inspection of Ship Hulls
USN	NAVSHIPS 250-1500-1 Rev. 9	1973	Welding Standard: PWR and Associated Systems
USN	NAVSHIPS 0900-006-9010	1966	Fabrication, Welding and Inspection of HY-80 Submarine Hulls
General Electric	P3TF2-56 RP-1020	1971	Fluorescent Penetrant Inspection Procedure for Equivalency Testing of Fluorescent Penetrant Inspection Materials
Pratt & Whitney Aircraft	FPM Code 1-7	1975	Fluorescent Penetrant Inspection Codes
Douglas Aircraft	DPS 4.707	1973	Penetrant Inspection, Fluorescent
Rolls Royce	TSD #594	1970	Overhaul Process 210 and 213
Bell Helicopter	BPS Rev. H-4089	1974	Penetrant Inspection
Boeing	BAC-5423	1974	Penetrant Method of Inspection
McDonnell Douglas	MMS-615	1973	Liquid Penetrant Systems High Sensitivity Water Washable
McDonnell Douglas	PS-21202	1971	Penetrant Inspection
USAF	T.O. 33B-1-1	1974	NDT Inspection Methods, Chapter 6, Fluorescent & Dye Penetrant Method

Issued by	Designation	Date of Issue	Title of Document
AEC Canada[a]		1973	Penetrant Inspection and Purity Requirements
ASTM	D 129-64(1973)	1964	Test for Sulfur in Petroleum Products (General Bomb Method)
ASTM	D 1552-64(1973)	1964	Test for Sulfur in Petroleum Products (High-Temperature Method)

[a] Atomic Energy Commission of Canada.

B. W. Boisvert[1]

Problems Encountered in Using Penetrant and Magnetic Particle Inspection Methods During Aircraft Maintenance

REFERENCE: Boisvert, B. W., "**Problems Encountered in Using Penetrant and Magnetic Particle Inspection Methods During Aircraft Maintenance,**" *Nondestructive Testing Standards—A Review, ASTM STP 624,* Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 172-176.

ABSTRACT: Penetrant and magnetic particle are the most widely used methods of nondestructive inspection performed during aircraft maintenance. This presentation will discuss briefly U.S. Air Force procedures in determining applications, developing specific techniques, and implementing inspections on a world-wide basis. This will provide the background necessary to understand the problem peculiar in maintaining military aircraft. The objective of this briefing is to describe the difficulties resulting from inadequate equipment/materials/process specifications and standards. General requirements necessary for the resolution of these difficulties will be defined.

KEY WORDS: nondestructive tests, standards, magnetic particle tests, penetrants

The purpose of this presentation is to discuss some of the problems caused by the lack of standards and uniform test procedures for magnetic particle and fluorescent penetrant inspection methods used during maintenance of military aircraft. The use of nondestructive methods during maintenance and, in particular, aircraft maintenance is considerably different from the testing and evaluation accomplished during materials production, fabrication, and manufacturing. These differences are the reason that the U.S. Air Force refers to nondestructive inspection (NDI) instead of the more familiar nondestructive testing (NDT) or newer generic, nondestructive evaluation (NDE). Actually, we have no contention with the words "testing" or "evaluation." In fact, in our depot and field operations, we occasionally perform NDT on materials and disassembled parts. The point remains that there are significant differences between inspection

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and testing. These differences can cause problems when applying standards and test procedures that do not allow for the peculiarities of maintenance inspection. In maintenance inspection, the concern is service-induced flaws which are either cracks or corrosion related. The flaws occur at the surface, and if they are fatigue cracks, they are oriented perpendicular to the stress flow. The optimum inspection method for a particular defect or component, or both, is not always used. This is because location, intervening structure, or accessibility may not permit the use of the optimum method. In performing aircraft maintenance, the equipment is carried to the flight line where the equipment and operator must be positioned in the most favorable orientation possible.

Compare these maintenance conditions to the testing practices used during raw material processing or manufacture. Here the material, part, or component is routed to or through a central testing location. The optimum test is employed with the item properly oriented for detection of a particular type of flaw or defect. Since there will be many identical items manufactured and tested, expensive jigs and fixtures can be constructed and the testing process can be semiautomated to reduce operator dependency. The size, weight, mobility, and versatility of the equipment is of no concern. These differences between maintenance inspection and testing during manufacture are cited not only to justify the distinction between the terms NDI and NDT but also to provide an understanding of some of the unique problems relating to the use of magnetic particle and penetrant methods during maintenance inspection.

General

Magnetic particle and fluorescent penetrant are our most used, or perhaps misused is more *apropos,* methods of inspection. While misused sounds rather strong, the rest of this presentation could be devoted to horror stories about the improper use of magnetic particle and penetrant inspection of critical parts. There are several reasons for this improper use and one is the apparent simplicity of the methods generates a feeling that they are infallible. This misunderstanding creates a false sense of security and a tendency to ignore basic requirements. In substantiation I would like to quote one of the conclusions from the Air Force Materials Laboratory (AFML) Technical Memorandum AFML/MX73-5.[2] This is the infamous magnetic particle interlaboratory test of eleven manufacturers where the average detection was only 47 percent of the existing flaws. The conclusion of concern is: "Observation indicated magnetic particle testing is still relegated to a low position of importance in most organizations, even though it is a major and perhaps the only quality check given some

[2] Gulley, L. R., Jr., "An Investigation of the Effectiveness of Magnetic Particle Testing," Technical Memorandum AFML/MX 73-5, Air Force Materials Laboratory, Oct. 1973.

parts." This same impression of simplicity and relatively low importance has resulted in deglamourization at the research level. The result is that fundamental and applied research projects in magnetic particle and penetrant methods are almost nonexistent. The same apathy exists in defining uniform method/equipment test procedures and standards. As a result, we are working with outmoded test procedures and few, if any, standards. This is especially relevent in the case of aircraft maintenance where applications and conditions are entirely different than those in manufacturing.

Magnetic Particle Inspection

Magnetic particle inspection is one of the oldest nondestructive methods with the initial work of Major W. E. Hoke, appropriately from the National Bureau of Standards, in the mid-1920s. This was followed closely by A. V. DeForest in 1928 to 1929 who, with F. B. Doane, incorporated Magnaflux Corp. in 1934 to manufacture and market magnetic particle inspection equipment. Practically all of the development work was accomplished during the 1935 to 1960 era. During the past 15 years, we have concentrated on improved equipment with little attention devoted to improvements in methods testing. The major problem in the application of magnetic particle inspection is the inability to measure the flux density reliably and economically in a critical location on a part to be inspected. Here is a method we have been using for 40 years without the capability of verifying that we are effectively accomplishing the inspection. The classical approach is to use 1000 A/in.^{2} of cross section. Yet this is true only for simple cross sections of straight bar or tubing. Unfortunately, there are very few parts with simple cross sections on an airplane. In 1972, Gregory et al[3] reported on the significance of part geometry. The report demonstrated that when a complex part was circular magnetized, the current would branch out into different directions at an intersection and the field at the intersection was zero. Normally, these intersections are highly stressed and if a crack existed in these areas, its presence would not be observed during circular magnetization regardless of current level. Again, I would like to refer to the AFML interlaboratory test of eleven manufacturers (see footnote 2). Nine of the eleven companies detected 30 to 60 percent of the existing flaws, one company detected only 19 percent, while the remaining company reached the 93 percent mark. The significance is that the company locating 40 of the 43 flaws (93 percent) was the only one that used a gaussmeter to determine direction and magnitude of magnetic fields when they developed their inspection procedures. Un-

[3] Gregory, C. A., Holmes, V. L., and Roehrs, R. J., *Materials Evaluation*, Vol. 30, No. 10, Oct. 1972.

[4] Kraska, I. R. and Prusinski, R. G., "Eddy Current Measurement of Magnetic Flux Density," Technical Report AFML-TR-72-115, Air Force Materials Laboratory, Nov. 1972.

doubtedly, if a simple, reliable, inexpensive device indicating local area flux intensities were used by all of the participating companies, there would have been a considerable difference in the number of flaws detected.

There have been several devices proposed that attempt to shunt some of the field from the part surface into an external specimen and then back into the part, for example Berthold Field Guage, Magnetic penetrameter, and Mu metal shims. In 1972, AFML released a report on the use of an eddy current instrument to measure field strength.[4] All of the proposed devices have serious drawbacks and are not used generally either in industry or in maintenance. I believe such a device to be the most immediate requirement for effective magnetic particle inspection.

Military Specification on Inspection Process, Magnetic Particle (MIL-I-6868E) provides several important test requirements for assuring adequate equipment performance. Unfortunately, the tests are oriented to stationary equipment using direct current for magnetization. The test for system effectiveness that consists of a tool steel ring with drilled holes at progressively increasing distances from the surface is concerned exclusively with direct-current magnetization. The word "unfortunately" is used since in maintenance we are looking for surface flaws only, and our primary method of magnetizing is with alternating current. The same problem of alternating versus direct current is encountered during the ammeter accuracy check. Direct-current ammeters require a simple calibrated ammeter/shunt arrangement. Alternating-current ammeters require a calibrated transformer arrangement that is expensive, difficult to use, and almost impossible to maintain in a calibrated status. The reference specification provides finite settings for pulse-length timers while in maintenance inspection magnetizing current duration depends upon the speed of the operator's uncalibrated thumb. No mention is made of the problems involved in measuring either the current or magnetic flux in longitudinal magnetizing coils and cable wraps. I think everyone agrees that dumping 6 000 A into a 5-turn coil does not produce 30 000-A turns except by description. The problem of inductance, even with a low ripple direct current is complicated further when the operator forms his coil from cable wraps. When we consider the use of alternating current flowing into the coil or cable wrap, we enter the realm of the totally unexplored.

The fluorescent particles used in the magnetic particle process are defined by Aeronautic Material Specifications (AMS). While this is an initial step, there is an urgent need to quantify the requirements better. Of immediate concern is the durability test that does not reproduce the solvent action that occurs in a stationary machine on the binder holding the fluorescent dye to the magnetic particles. Unfortunately, it took a landing gear failure to discover the discrepancy when inadequate magnetic particle inspection was listed as a contributing factor in an aircraft accident report.

Penetrant Inspection

The penetrant inspection process is perhaps in even worse shape than magnetic particle with respect to standards and test specifications. The Military Specification on Inspection Materials, Penetrant (MIL-I-25135), first issued 6 Aug. 1956, contained four categories of penetrant materials. These were one type of visible dye, one type water washable fluorescent, plus a "normal" and a "high" sensitivity postemulsifiable fluorescent material. The latest Military Specification on Inspection Materials, Penetrants (MIL-I-25135C), issued 21 Oct. 1959, with Amendment 3, dated 1 June 1964, lists seven groups, three visible materials, one water washable fluorescent, two postemulsifiable fluorescents (normal and high sensitivity), plus a solvent removable spray can family. This history is cited to show that in 20 years we have been unable to define sensitivity except in the general terms "normal" and "high." There have been many tests proposed: heat cracked aluminum blocks, fine wire tightly wound on a precision mandrel, the Ohio State/Monsanto cracked nickel-chromium plated panels, and crazed anodized coatings, to name a few. All have problems that prevent their use in objectively categorizing penetrant materials into finite sensitivity ranges. In the military, we have a special problem called a qualified products list. According to our procurement regulations, all products listed under a single group perform equally, and criteria for award of contract is based solely on price. This obviously becomes a case of apples versus bananas, with the high performing and more costly materials coming out short. We desperately need some standard and uniform test method to allow rational categorizing of various materials.

Conclusion

Magnetic particle and penetrant inspection are two of the oldest and most widely used NDT methods. They are also the most likely candidates for uniform test standards and methods. Any work in developing standards and test methods must consider maintenance applications in addition to materials production and new manufacture.

L. T. Detlor[1]

Application of Magnetic Particle and Liquid Penetrant Methodology in Petroleum Refineries and Petrochemical Plants

REFERENCE: Detlor, L. T., "**Application of Magnetic Particle and Liquid Penetrant Methodology in Petroleum Refineries and Petrochemical Plants,**" *Nondestructive Testing Standards—A Review, ASTM STP 624,* Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 177–181.

ABSTRACT: The magnetic particle and liquid penetrant methods are used routinely in the hydrocarbon processing industries to find surface flaws that usually are not evident visually. Some flaws originate in the material and during fabrication of equipment. Others originate due to service conditions and are often the product of interaction between mechanically induced stresses and corrosion. The competence of those using the methods is a capability factor. Both methods have pluses and minuses in their capability. Finally there probably are things that can be done to improve the effectiveness of the system used.

KEY WORDS: nondestructive tests, standards, magnetic particle tests, penetrants, system qualification

The petroleum refining and petrochemical industry rely on magnetic particle and liquid penetrant methodology to examine a wide variety of items. With perhaps a few exceptions, standard, manually applied techniques are used. Before considering any details regarding these methods, two general statements are necessary regarding their overall capabilities. First, both methods can be considered as "super" methods of surface examination, that is, super when compared with visual examination. Secondly, although there are significant differences in the overall capabilities of the two methods, the American Society for Mechanical Engineers (ASME) Boiler and Pressure Vessel Code Committees have treated them as equals thus far.

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Background

Later consideration of the methods can be simplified by the following condensed descriptions. The magnetic particle method, reduced to oversimplified terms, depends on the disturbance of a magnetic field induced in the part or piece by a flaw to the extent that a leakage field is created on the surface. Small ferromagnetic particles sprinkled over the leakage field will align themselves over the magnetic poles that exist, indicating the presence of the flaw. There are several standard ways of enhancing the indication.

The liquid penetrant method utilizes the ability of the flaw to trap enough of a suitable liquid so that after the excess penetrant is removed from the surface, that remaining in the reservoir will bleed out, staining the surface. The bleed out, of course, indicates the presence of the flaw. Quite a number of enhancements can be employed to indicate that bleed out has occurred.

The methodology is applied for two basic reasons. The first reason is to assure that the surfaces of finished material and fabricated components are free from injurious mechanical discontinuities before shipment from the manufacturer to the site or before placing in service if fabricated at the site. In certain instances, the methods also are used to make checks during fabrication to avoid more extensive repairs later or to evaluate quality that cannot be determined later without difficulty. These comments should not be interpreted as meaning that all items are examined. The decision to require they be used is service dependent with safety always being a consideration.

The second reason is to assess the condition of the operational equipment during a downtime or turnaround. Borrowing a term from the nuclear power industry, these examinations where the equipment is checked in place could be called in-service examinations. A distinction should be made between such an examination during unit outage and those that are done while the unit is operating. The latter check would be considered on-stream inspection in the petroleum-petrochemical industry.

Process unit operation in the hydrocarbon processing industry generates material discontinuities by two mechanisms which sometimes interact. Most everyone will recognize the following as sources of surface discontinuities:

- Fatigue cracks from mechanical and thermal cycling
- Stress discontinuities from surface or metallurgical notches
- Unsuitable choice of weld filler metal joining dissimilar metals for the service condition
- Over stressing

Another set of conditions exist in these plants that creates injurious flaws through corrosion and material embrittlement. They include: chemical compounds in the hydrocarbon process streams that contain sulfur or chlorine as well as some metals, hydrogen, in the process stream or made available as a product of corrosion, and caustics and acids used in processing.

These react with the materials of construction, sometimes in combination with stresses from mechanical causes, in several ways to create cracks or crack-like crevices that can be found by magnetic particle or liquid penetrant techniques when the methodology is used properly.

One more point needs to be made in evaluating how the hydrocarbon processing industry uses these methods of examining surfaces for defects. Although there is a continuous need for the methodology, each application is usually different from the ones that immediately proceeded it. The use of automated equipment is not feasible. This requires knowledgeable personnel who understand:

- What they are looking for
- How the flaws can best be found
- What the consequences are if they do not find what is there

With this background, we now can look at some of the important penetrameters of the methodology. The important parameters, as used here, mean those major items in the application of the method that make their use a success or failure.

Parameters for Magnetic Particle

The materials must be ferromagnetic. This can take care of all the ferritic and martensitic alloys. The interpretator/user of the technique must understand the basics of the method, that is, that the flux field must be interrupted by the flaw and the subsequent leakage field must be evident on the surface. Closely associated with these principles is how to introduce the flux field and to assure that is has sufficient strength. Equally important is the proper application of the particles.

Although all the emphasis has been on the ability of this method to indicate surface flaws, there is a limited capability for indicating discontinuities just under the surface, perhaps within 1/8 in. (3 mm). The ability of the leakage field to reach the surface is not always predictable. The interpretator must know the characteristic response of the system to the various types of flaws that will be encountered. Similarly, the typical causes for false indications must be recognizable.

One of the advantages of this method is that the surface being examined does not have to be clean to bare metal. Experience indicates that a thin, tight coat of paint or mill scale up to perhaps 0.004 in. (0.1 mm) thick does not interfere with the examination.

There are other disadvantages with the method besides the need for magnetizable material. If magnetizing current is introduced by prods, the possibility of damage by arc burns exists. On steels like the low chromes, an arc burn will create a hard spot which later may be the nucleus for a crack. Residual magnetism remaining from a magnetization can create problems in rotating machinery if the field strength is not reduced sufficiently.

Parameters for Liquid Penetrant Examination

The surface to be examined must be clean. This includes removal of enough "soil" from any existing flaws so that some penetrant will be trapped. This is not always easy. This and the following points are important when pieces or parts that have been taken out of service are examined. Examples would be gas-turbine and steam-turbine blades. It is understood that one company subjects gas turbine blades to a thermal cycle before examination to break the bond of any oxides that may be filling or masking a flaw. Further, the surface texture must not be smeared or peened over so that the discontinuities sought are closed over.

The penetrant system selected must be suitable for the material being examined. For example, a post emulsification system would work very well on the rough, unmachined outer surface of a centrifugally cast tube.

The penetrant system must be applied in the specified sequence in accordance with the procedure. An understanding of the basics of this method is also important because there are times when minor changes in procedure will provide a stronger indication.

All the liquid penetrant systems will work on virtually all the metal materials of construction used in the petroleum and petrochemical industry. They also will work on some of the nonmetallics provided the surfaces were not made porous intentionally. The solvent base system enjoys the advantage of high and easy portability, a nice thing to have when the problem is high in the air, inside a vessel.

The necessity to have clean, bare metal surfaces is sometimes a handicap for liquid penetrant usage. If the material can be magnetized, this is a good reason to use magnetic particle examination. Use of a fluorescent system in the field also can be a problem unless the area can be darkened to make use of the "black light" effective. In the field, work can be done at night but this can create problems too.

Future Needs

The following comments are personal beliefs, based on experiences in the shop, in the field, and at the desk over an extended period of time, as well as trying to help create written documents on the methodology for use in ASME and American Society for Testing and Materials (ASTM) publications.

Currently, there is great interest in written procedures and having the methodology applied by properly qualified personnel. Some may feel these requirements are being overemphasized outside the nuclear energy area. The real concern has to be that of assuring that the specified technique is applied correctly although it is recognized that interpretation is also important.

To this end, there should be a way to make both systems more self-qualifying. To illustrate, a comparison with industrial radiography requirements can be made. Basically, if the image quality indicator (IQI), the penetrameter outline and the essential hole or specified wire can be seen and the developed film has the correct density, the technique can be considered as qualified for many applications. For magnetic particle techniques, mandatory use of the field strength indicator outlined on ASTM Magnetic Particle Examination of Steel Forgings (A 275-76) may be the answer or someone may have a better idea.

For the penetrant systems, the currently recognized aluminum test block and the Ohio State University chrome plated test panel does not seem to offer universal satisfaction. A lot of work has been done in this area. As an example, it was recently learned that one company has a test panel that utilizes a 10-mm Brinell hardness ball to create reproducible flaws.

The requirements for the powders used with both the dry and wet magnetic particle methods are not spelled out adequately. How do you convince a metal fabricating shop in South America or Sicily that they should not be using pulverized mill scale or iron filings to find cracks?

Some of the work done for Section V of the *ASME Boiler and Pressure Vessel Code* has demonstrated how grit or shot blasting or machining can close or smear over a slit in a test block assembly so that penetrant techniques do not disclose it. This fact needs more development where castings are involved.

Summary

Summarizing, the hydrocarbon processing industry relies on the magnetic particle and liquid penetrant methods of material examination for finding surface located flaws. The competence of those who actually apply the selected procedure is a factor in what material discontinuities are found or missed. Each method has its pluses and minuses. For new material and equipment, the liquid penetrant method probably has the greatest appeal but it may not always be the best. There are things that need to be done to increase the effectiveness of the methodology.

R. R. Hardison[1]

Magnetic Particle and Liquid Penetrant Testing in the Shipbuilding Industry

REFERENCE: Hardison, R. R., "**Magnetic Particle and Liquid Penetrant Testing in the Shipbuilding Industry**," *Nondestructive Testing Standards—A Review, ASTM STP 624,* Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 182-188.

ABSTRACT: This paper discusses the variations in inspection results which can be obtained through the use of mixing variables within the allowable specification requirements. The need to standardize field indicators also is discussed. The ability to reproduce inspections, for example, during audits, without more rigid standardization is questioned. The base specification for the above discussion will be Military Standard on Nondestructive Testing Requirements for Metals (MIL-STD 271, D and E). Also, a brief dissertation concerning the lack of magnetic particle/liquid penetrant testing requirements as applied to commercial shipbuilding is given. Finally, the paper discusses magnetic particle/liquid penetrant acceptance standards and the lack of statistical or engineering data, or both, to support their existance.

KEY WORDS: nondestructive tests, standards, magnetic particle tests, penetrants, shipbuilding

The purpose of this paper is to discuss briefly specific areas of the applicable codes and specifications dealing with magnetic particle testing and liquid penetrant testing which could be considered in need of further standardization. Since this is to be a brief presentation, only some of the areas which the author considers the most significant will be discussed. Although this paper is concerned primarily with nonnuclear shipbuilding standards, the problems discussed are germane to other standards throughout industry. Solutions to the problem areas discussed by this paper, in some cases, will not be offered. The purpose of this symosium is not to necessarily give solutions, but rather to stimulate interest and promote the need for additional thought/research.

First, this paper will discuss the primary codes applicable to the commercial shipbuilding industry. Following this, two revisions of the primary

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nonnuclear Navy Shipbuilding Standard, Military Standard on Nondestructive Testing Requirements for Metals, (MIL-STD-271) will be discussed, and finally, some comments are given regarding magnetic particle and liquid penetrant testing acceptance criteria.

Commercial Shipbuilding

In the commercial shipbuilding industry, very little magnetic particle or liquid penetrant inspection is invoked. The primary governing rules are those imposed by the American Bureau of Shipping (ABS) and the U.S. Coast Guard. The ABS rules require magnetic particle inspection of selected castings only. The ABS has no standards for magnetic particle/liquid penetrant inspection of any material. "Catchall" words within the ABS rules do leave a right to request magnetic particle/liquid penetrant inspection of weldments, but this right is not exercised generally. The U.S. Coast Guard also must issue a certificate for each commercial ship, therefore, they have some requirements in the piping and pressure vessel area. Magnetic particle and liquid penetrant inspection invoked by the U.S. Coast Guard is performed in accordance with Section VIII of the American Society of Mechanical Engineers *(ASME) Boiler and Pressure Vessel Code* and acceptance standards are established by the U.S. Coast Guard. Again, no standards exist for how to do or for acceptance by the ABS. Since the only area in commercial shipbuilding where standards exist is in the piping and pressure vessel area and since these standards are being covered elsewhere in these presentations, the commercial shipbuilding area will not be discussed further except for the following comment. It is felt by the author that magnetic particle and liquid penetrant inspections in the structural welding area would be meaningful and possibly could reduce the cost in the commercial shipbuilding industry by replacing some of the more costly inspections being performed in American shipyards. These surface inspections, complimented by soundness inspections by radiography or ultrasonics if properly and systematically invoked, could provide the customer with necessary quality control and a high degree of confidence in the fabrication of his ship. Existing standards invoked in commercial welding areas could be made applicable to welds in the structure of ships.

Navy Shipbuilding

The primary how-to-do specification in U.S. Navy shipbuilding in the nonnuclear area is MIL-STD-271. Presently, work is being done to the "D" revision of this standard, however, there is an "E" revision of the document that has been published. MIL-STD-271D is invoked and modified by various fabrication documents or the ships detailed specifications, or both. This standard is applicable to structural and piping weldments, castings, and forgings. Due to the brevity of this presentation, discussion will center on the magnetic particle testing process.

Figure 1 is a picture of the magnetic field indicator required by MIL-STD-271. The indicators are identical in both revisions of the document with the exception that MIL-STD-271E puts a limitation of 1/32 in. on the gap between the pie shaped segments. MIL-STD-271D allows the use of this indicator, for circular magnetization using the wet method, "in establishing a suitable flux." However, for prod inspection MIL-STD-271D has a specific requirement for the magnetizing current to be "computed on the basis of approximately 100 amperes per inch of prod spacing." MIL-STD-271E, however, states, "The optimum current setting shall be determined by means of a magnetic field indicator . . . a suitable current setting is obtained when clearly defined lines of magnetic particles form across the face of the indicator . . . ." For prod inspection specifically, MIL-STD-271E further states, ". . . the magnetizing current . . . *should* be computed on the basis of approximately 100 amperes per inch of prod spacing . . . ." The later revision of MIL-STD-271, therefore, has taken a decided turn toward the dependence of a field indicator to establish a suitable flux.

We recently ran some experiments using the MIL-STD-271 indicator. It was found that a good indication could be obtained by the indicators using the prod method on low alloy steel with approximately 20 A/in. The indicator was evaluated with an alternating-current yoke and a strong indication was obtained.

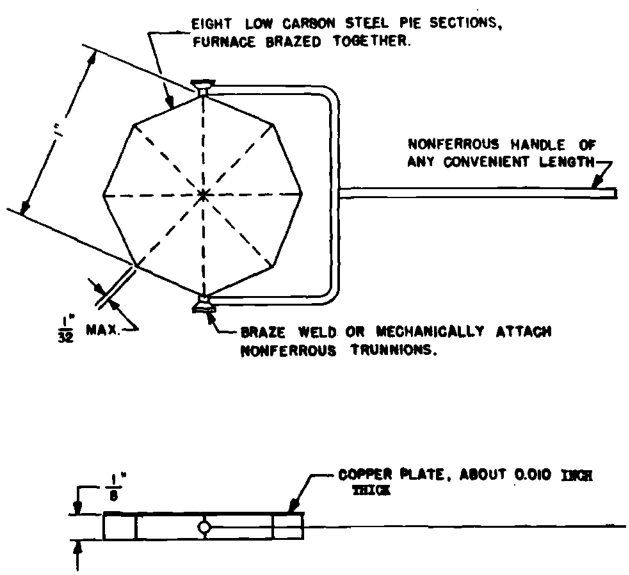

FIG. 1—*Magnetic field indicator.*

What type of information does the indicator yield? If the alternating-current yoke produces a strong indication, then certainly the field indicator has little value in establishing the detectability of subsurface discontinuities. Also, since the pie segments of the indicator represent rather gross discontinuities, no useful quantitative information is obtained regarding the sensitivity of the test. It would appear that the MIL-STD-271 field indicator supplies two types of information, both of which are qualitative in nature: (*a*) the approximate direction of the field, and (*b*) a magnetic field is present of some minimal threshhold value. In the nondestructive testing (NDT) laboratory, it has been demonstrated, with at least two indicators of the MIL-STD-271 design, that this threshhold value is approximately 20 A/in. for half-wave rectified current. The threshhold value in ampere turns is not known, but an alternating-current yoke with a lifting capacity of at least 10 lb will produce an adequate field to obtain an indication on the field indicator.

Does the use of the field indicator establish that an adequate flux is being generated to perform the inspection? MIL-STD-271E recommends that 100 A/in. of prod spacing be used, but at the same time, requires the use of a field indicator to determine the optimum current setting. Experiments have shown already that adequate indications were obtained using the field indicator with 20 A/in. of prod spacing.

Studies were not completed to determine the effects of the design variables allowed in the fabrication of the MIL-STD-271 field indicator. For example, the "eight low carbon steel pie sections" leave room for variation in deciding exactly what is low carbon steel. It would be better to establish a required permeability value or to specify a particular material. The E revision has established that the sections are to be brazed with no more than 1/32-in. gap between sections. The D revision does not limit the gap.

There are several other areas within MIL-STD-271 that are in need of standardization consideration which are not necessarily confined to that standard and which are worth mentioning:

1. MIL-STD-271D and E do not specify any quantitative requirements regarding magnetic particle size, shape, purity, or magnetic properties. There are some general words having to do with "nontoxic, finely divided ferromagnetic material of high permeability and low retentivity, free from deleterious rust, grease, paint, dirt, or other material. . . . Particles shall be of such size, shape, and color as to provide adequate sensitivity and contrast. . . ." There was at least one problem experienced by another shipyard some time ago where it was discovered that a supplier had furnished that company with magnetic particles which were oval in shape, contaminated with nonferromagnetic material, and did not provide adequate sensitivity. Revision E of MIL-STD-271 does help alleviate this problem by

requiring the activities to prove the ability of their written procedure by performing tests on objects containing the smallest rejectable surface defects which will require detection (these defects may be artificial or natural). Also, for the dry method, the E revision requires that a proof test be made on each lot of particles by application on a weldment in the vertical position to detect known discontinuities 1/16 in. and longer.

2. Equipment calibration requirements are nonexistent in MIL-STD-271D. The E revision picked up the ASME Section V requirements, that is:
   a. Full wave direct-current rectification units—the equipment meter shall agree within 5 percent of the current measured by the calibration meter (hooked up at the prods).
   b. Half-wave direct-current rectification single phase units—the direct-current ammeter will read half the value of the rectified direct-current magnetizing current.
   c. Yoke equipment—with pole spacing from 3 to 6 in., the lifting power on carbon or low alloy steel shall be 10 lb for alternating-current yokes and 40 lb for direct-current yokes.

   It should be specified when calibrating equipment meters whether peak current is being measured or average values. Average values of current will be approximately equal to peak current value/π.

   It is not known by the author where the 10 and 40-lb lifting tests for yokes originated or what physical data support these values. However, it would seem that the absolute parameter of pounds lifting capacity would not suffice. Flux density is the important parameter. If two different yokes both have a 10-lb lifting capacity but the area under the prod tips are greater for one than for the other, then the flux density in the part is not going to be the same for both.

3. Both of the previously mentioned problems indicate the need for a quantitative measuring stick to determine the field strength within a part. Better yet, what is the required field strength in order to detect undesirable discontinuities within a part? MIL-STD-271E requires a procedure check to establish that the smallest rejectable defect is detected using artificial or known surface defects. It is known that the use of alternating current is excellent for detecting surface defects, yet codes continually require the use of direct current. It would be inferred then that subsurface discontinuity detection is desirable; yet there is no quantitative tool to measure this detectability.

   As a minimum, two problem solutions are in order to more fully standardize discontinuity detectability (namely, test sensitivity):
   a. What are the size, shape, orientation, and location within a part

of the minimum unacceptable discontinuity to be detected (within equipment limitations)?

b. A device that can be utilized physically to assure the inspector the required test sensitivity to detect if this condition is present during inspection.

The need for the development of sensitivity standards is not unique to magnetic particle inspection; the same holds true for liquid penetrant inspection. To ensure consistent inspection results between activities using the same basic specifications, such standards are an absolute necessity.

Acceptance Criteria

Military Standard on Surface Inspection Acceptance Standards for Metals (NAVSHIPS 0900-003-8000) is used widely throughout U.S. Navy shipbuilding. In general, the acceptance criteria for weld magnetic particle testing is "no linear indications over 1/16 inch." In liquid penetrant testing rounded indications and differing classes of acceptance are considered. For Class 1 the allowed total accumulated rounded indications area equals 0.375 percent of the weld surface area; for Class 2, 0.5 percent; and for Class 3, 0.75 percent (combinations of maximum size and number of indications are given). ASME Section VIII requirements for magnetic particle inspection are somewhat more stringent in that *all* linear indications must be removed and no definition of linear is given. For liquid penetrant inspection, Section VIII requires the removal of all relevant linear indications (linear defined as length X3 the width and major dimension greater than 1/16 in.) and four or more rounded indications in a line separated by 1/16 in. or less. The magnetic particle acceptance requirements for the U.S. Navy are somewhat less stringent whereas the liquid penetrant requirements are more stringent than those imposed by ASME. The point is that there appears to be no direct uniformity when looking at various specification acceptance criteria. What do these acceptance criteria represent? Do they relate directly to product design and reliability or do they simply represent different levels of acceptable/unacceptable workmanship? Since a problem with product failures is not being experienced, it could be assumed that today's acceptance criteria would lean to the conservative side. This being the assumption, how many dollars are being poured down the drain by being too conservative? Is this country possibly wasting millions (perhaps billions) of dollars correcting conditions to cause adherence to a set of words that have no specific merit? This symposium, of course, is interested in defining "where we are and where we need to go" in the area of NDT standards. Acceptance criteria is one area where standards exist, but the question arises—how does one evaluate the merits of these standards?

Recommendations

1. The ABS should evaluate the need for magnetic particle/liquid penetrant inspection standards in the commercial shipbuilding industry to be used as complimentary or possibly supplementary inspections to the soundness inspections now being performed.

2. MIL-STD-271E is an improved document insofar as equipment standardization over the D revision. However, the use of a field indicator to establish the "optimum field" is incorrect. Even with the improvement, additional standardization is required. Sensitivity standards yielding quantitative results or based on quantitative research need to be developed for both magnetic particle and liquid penetrant inspection.

3. Acceptance standards for magnetic particle/liquid penetrant testing should be based on engineering data which have direct correlation to product reliability.

W. C. Plumstead[1]

Specification/Code Syndrome

REFERENCE: Plumstead, W. C., "**Specification/Code Syndrome,**" *Nondestructive Testing Standards—A Review, ASTM STP 624,* Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 189–193.

ABSTRACT: This presentation intends to show a need for fewer standards and specifications from the independent laboratory viewpoint.

Although the independent testing laboratory attempts to maintain an adequate library of specifications, standards, codes, and procedures, it is not uncommon to receive requests to perform tests and evaluate results according to a completely unfamiliar document. New variables introduce a potential for error.

The overall results of liquid penetrant inspection, magnetic particle inspection, and the other nondestructive testing methods would benefit if fewer documents existed which also address the engineering principles behind the testing procedures and acceptance criteria incorporated into the document. Documents of this nature would provide better test performance and more accurate results just as a result of the familiarity created. Personnel training effectiveness would improve with less supervisory control.

KEY WORDS: nondestructive tests, standards, technical writing

The multitude of documents on nondestructive testing (NDT) is a great problem to the commercial NDT operation. It is not uncommon to receive an inquiry for NDT services to be performed according to a document with an unfamiliar designation. In some cases, it is difficult even to determine where to secure this document.

This paper will attempt to illustrate the situation and the problems associated with a commercial NDT operation. Alternatives will be suggested that would make commercial NDT operations more manageable, produce more reliable results, and operate at lower costs.

The Problem

The many documents existing to control NDT operations were probably generated with good intentions—ultimately to produce reliable results of

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desired sensitivity. Reliability is related closely to repeatability. If performance of a NDT method can be repeated to produce the same result, then reliability generally can be assumed. In radiography, an image quality indicator or penetrameter indicates reliability of technique quality. The other NDT methods require a strict control of each step to assure reliability or repeatability. Strict control is necessary because NDT is an operator-oriented activity. Human judgement varies with the individual; therefore, it is necessary to control work procedures to produce reliability.

Unfortunately, a variety of technical groups have recognized the need for controls in NDT operations and apparently acted independently. The resulting proliferation of standards has introduced more variables. These additional variables can be translated into additional cost. Since more variables introduce greater potential for error, more supervision and training is required; also, the many documents must be updated continually.

A brief look will be taken at some of the requirements to consider whether a need for so many documents does exist. Some of the test essentials will be compared to provide an indication of the situation because comprehensive analysis would not seem to serve our purpose here.

Differences exist in magnetic particle inspection from several documents in such areas as prod spacing, current ranges, type of magnetization, black light calibration, etc., as shown in Table 1. Table 2 compares documents in liquid penetrant inspection and shows that differences exist in black light calibration, water wash temperature and pressure, and temperature of the part under inspection.

Some documents have special requirements. The Military Standard on Penetrant Method of Inspection (MIL-I-6866B) requires that acceptable parts be identified. Several documents require specific personnel qualification and certification. Military Standard on Nondestructive Testing Requirements for Metals (MIL-STD-271E) requires a test of the dry powder. It must be capable of showing a $\frac{1}{16}$-in.-linear indication in the vertical position. Also the ammeter must be calibrated within 5 percent at the time of purchase, every three months, and after each servicing. Tables are attached which provide several specific areas of commonality or differences in magnetic particle and liquid penetrant inspection. I wonder if any real technical meaning is associated with these differences.

There is no apparent trend to reduce the number of documents that we must use. Certainly a redundance exists to some extent in all of the documents. Because of the multitude of documents, a specified document must be researched to determine the essential variables controlled by that document—this introduces cost and a potential for error, because something can be overlooked. The requirements must be communicated to the technician performing the test—more cost and potential for error. The technician cannot perform as efficiently if some requirements are un-

TABLE 1—*Magnetic particle inspection.*

Document	Method	Medium	Prod Spacing	Current
ASME Boiler and Pressure Vessel Code, Nondestructive Examination, Section V, 1974	continuous	adequate contrast wet or dry	1. maximum 8 in. less than 3 in. not recommended 2. if greater than 25 V do not use copper tips due to copper penetration	1. direct or rectified 2. less than ¾ in., 100 to 125 A/in. 3. ¾ in. or more 90 to 110 A/in.
Military Standard on Nondestructive Testing Requirements for metals (MIL-STD-271E)	continuous	adequate contrast wet or dry	2 to 8 in.	1. direct or rectified 100 A/in. 2. less than ¾ in. thick Spacing, in.: 2 to 4 — 200 to 300; 4 to 6 — 300 to 400; 6 to 8 — 400 to 600 3. ¾ in. or more Spacing, in.: 2 to 4 — 300 to 400; 4 to 6 — 400 to 600; 6 to 8 — 600 to 800
ASTM Dry Powder Magnetic Particle Inspection E 109-63(1976)	1. continuous 2. Appendix A-1 allows residual 3. prods only	dry powder	2 to 8 in.	1. direct or rectified 2. table same as MIL-STD 271E, amps versus prod spacing 3. Appendix A1 allows alternating current
American Welding Society Structural Welding Code (AWS D1-1-72)	(references, ASTM Method E 109-63(1971))			

TABLE 2—*Liquid penetrant inspection.*

Document	Part Temperatures	Water Wash	Calibration of Black Light
ASME Boiler and Pressure Vessel Code, Nondestructive Examination, ASME Section V, 1974	60 to 125°F may qualify others	water pressure less than 50 psi at less than 110°F	90 fc 3300 to 3900 Å
Military Standard on Penetrant Method of Inspection (MIL-I-6866B)	up to 150°F	coarse spray	90 fc at 15 in.
Military Standard on Nondestructive Testing Requirements for metals (MIL-STD-271E)	50 to 100°F	water pressure less than 40 psi at temperature less than 120°F	100-W Hg floodlamp, filtered to allow only ultraviolet rays
ASTM Recommended Practice for Liquid Penetrant Inspection Method (E 165-75)	up to 125°F	coarse spray not to exceed 50 psi between 60 to 110°F	minimum 800 $\mu W/cm^2$ on surface of part measured with suitable black light meter

familiar—more cost and potential for error. Controls must be established to reduce error—more cost.

Errors in performance and evaluation of tests produce costs. Rework is an expensive penalty to pay, and some rework is created, in my opinion, because we deal with such a large variety of requirements. We do not have a chance to form habits through familiarization. Documents are changing too often. We not only have to research specific documents but, in addition, we presently must learn how to interpret the document because the words differ from one document to another. We are researching documents continually to determine requirements. Supervision could be more effective if personnel were performing repetitious work. Our personnel require too much personal attention of the supervisor or long experience to produce the proper results.

What Action

It seems feasible that many documents could be eliminated by consolidation. Perhaps several representatives of each document producing group should form a committee for the review of existing documents and then produce fewer, more meaningful documents. Documents may be required for specific types of inspection due to differences in sensitivity requirements. Categories that might be considered are: manufacturing inspection, in-service inspection, and raw material inspection; a document for each category may be sufficient. Raw material and manufacturing inspection would be searching for inherent defects, and in-service inspection would search for fatigue or propagating defects. Based on the analysis of this research, it is concluded that the number of NDT documents that have been generated have contributed to unnecessary costs of NDT. No one can be familiar with all of the NDT documents available, and unfamiliarity creates a potential for error. Training and experience of qualified technicians could be reduced if documents were standardized and results would be improved at the same time.

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Penetrant Inspection Standards

REFERENCE: Packman, P. F., Hardy, G., and Malpani, J. K., "**Penetrant Inspection Standards,**" *Nondestructive Testing Standards—A Review, ASTM STP 624,* Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 194–210.

ABSTRACT: The purpose of this paper is to review some of the quantitative techniques that have been used for the evaluation of penetrant systems and to present an analysis technique based on analysis of variance (ANOVA) that appears to have a potential for rating penetrants.

The paper covers five areas: quantitative penetrant methods, two-fold congruency evaluation, the limitations on the reuse of the specimens, the influence of threshold visibility on evaluation of penetrants, and crack line intersection counting and evaluation of the crack line intersection data by ANOVA to evaluate the effects of primary and secondary influencing variables.

KEY WORDS: nondestructive tests, standards, penetrameters (radiation), crack detection, process variables, penetrant inspection procedures

The purpose of this paper is to present and discuss some of the factors that are involved in the design and evaluation of a penetrant inspection specimen that could be used as a quantitative ranking system. At the present time, there is no commonly accepted method for the evaluation of penetrant sensitivities, primarily because there is no available acceptable standard for use as a comparison. Although several potentially useable approaches have been suggested, there are serious doubts that there would ever be one acceptable penetrant standard that could encompass the wide range of penetrants and materials and procedures that use penetrant inspections.

The primary industrial standard is the Aerospace Military Specification on Fluorescent Penetrant Inspection (AMS 2645). These specifications control the penetrant material by specifying such physical parameters as ash, color, fluorescence, flash point, precipitation number, viscosity, and water content. These tests are primarily for the quality control of the

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product and do not relate directly to the sensitivity of the fluorescent materials as to their ability to detect small surface cracks.

The two specifications for penetrant inspection are the Military Standard on the Penetrant Method of Inspection (MIL I 6866), which is primarily procedural but cross indexes the Military Standard on Aircraft Structural Integrity Program Requirements (MIL I 25135), which establishes aluminum quenched cracked panels to rate penetrant sensitivities. However, the test procedure should be considered as only relative, comparing one penetrant with another, rather than as a true quantitative ranking process.

Most high performance penetrant systems are fluorescent in nature, and the essential performance features of these systems are expressible as a function of the fluorescent response. Failure of the entrapped material to fluoresce properly or combinations of materials within the defect to quench the fluorescence would result in a process that has less than maximum detection capabilities. The physical-chemical behavior of the penetrant, particularly through its inability to enter into the defect, or to remain within the defect during subsequent washing, and other steps necessary during the penetrant process also will result in a penetrant process that cannot have the desired high sensitiviy. While measurements of the fluorescent threshold and those factors influencing the flaw entrapment efficiency are of immediate concern in quantifying penetrant systems, they cannot be dealt with within the scope of this article.

This paper is concerned primarily with the detectability of defects by penetrant systems and a quantitative measurement of the ability of the penetrant to detect small defects. The ultimate objective of such a measure would be to develop some ranking system or scale against which a wide range of penetrants could be evaluated. The results then would be applicable to evaluation and acceptance of penetrant systems only as far as the quantitative ranking applies to the particular type of inspection standard being used and would not be expected to provide a total ranking of penetrants under other operating conditions or for use on other materials.

This is rather significant, for one would not expect a penetrant system that was appropriate for plated chrome cracked plates to be appropriate for titanium surface defects on a surface with a machined finish. The wetting conditions for the penetrant would be different, the amount of washing and the type of precleaning would be significantly different, and as can be demonstrated these factors exert a significant influence on the reliability of the penetrant system.

This paper is divided into five sections as follows:

1. Quantitative penetrant evaluation methods, which review some of the specimens that have been used for the evaluation of penetrant performance and the influence of several penetrant properties.

2. Twofold congruency method, which is a quantitative method used for ranking penetrant systems

3. Reuse of the specimens
4. Human visibility threshold influencing the standard evaluation system
5. Analysis of variance combined with crack line intersection counting as a penetrant rating procedure

Table 1 presents a summary of the types of tests and the specimens used in recent evaluation processes for penetrants. More complete details are given in the body of the text.

Quantitative Penetrant Evaluation Methods

An early procedure for evaluating penetrant materials was presented by Miller [*1*][3] using a set of precision ground sleaves fitted onto a threaded bolt. When the bolt was tightened to 30 ft·lb, all of the dye penetrants inspected gave distinct high-contrast indications of the sleave interface. If, however, the torque applied to the system was 200 ft·lb, the dye penetrant indications of the sleave interface became much more indistinct for one of the penetrants while the other dye penetrants' radiations remained relatively distinct. This showed that one of the penetrant systems, at this time (1958), had a lower degree of sensitivity to this type of defect. No tests were presented on fluorescent penetrants.

McCauley and Van Winkle [*3,4*] conducted extensive studies into the relationships between the properties of penetrants and the observable detection behavior of penetrants. They developed a standard chrome-plated brass plate which can be cracked to produce a pattern of surface defects. The panels are divided into three categories, depending upon the width of the defects: coarse (500 μin.), medium (90 to 130 μin.) and fine (19 μin.). These panels are available from a number of sources. They developed the concept of a crack detection efficiency (CDE) based on the ratio of the number of cracks per linear inch detected by the penetrant to a measure of the cracks per linear inch counted under 100 magnification with a microscope. Table 2 shows some of their measurements of CDE of several penetrants and compared the values to other penetrant properties such as static penetrability performance (SPP), the absorption coefficient, *Kc*, and the fluorescent efficiency, *Q*. In addition, a comparison was made with a parameter consisting of the absorption coefficient times the fluorescent efficiency.

It can be seen that there does not appear to be any direct correlation between crack detection efficiency and any of the physical properties of the penetrant. The penetrant system with the highest crack detection efficiency (91 percent) had a *KcQ* factor significantly lower than three of the other penetrants that ranked lower in crack detection efficiency. The

[3] The italic numbers in brackets refer to the list of references appended to this paper.

TABLE 1—*Summary of recent penetrant studies leading to penetrant standards.*

Specimen Type	Reference	Study	Measure[a]
Chrome cracked brass	Sherwin [2]	effect of dwell mode	qual.
Chrome cracked brass	McCalley and Van Winkle [3,4]	crack detection efficiency	quant.
Chrome cracked brass	Monsanto [3,4]	crack detection efficiency	qual.
Ti6A1-4V SCC	Lord and Hollaway [5]	penetrant efficiency	qual.
Ti6A1-4V fat	Lord and Hollaway	penetrant efficiency	qual.
Ti6-6-25n forge porosity	Lord and Hollaway	penetrant efficiency	qual.
Chrome cracked steel	Fricker [6]	developer and penetrant	qual.
Titanium NaCl crack			
Fatigue cracked panel	Bouricki [7]	effect of wash times on brightness	quant.
Fatigue cracked cylinders	Packman [8]	effect of crack size	quant.
7075-T6 aluminum		accuracy of crack length	quant.
4335V mod steel			
Fatigue cracked panels	Gray (B-1)	effect of crack size	quant.
aluminum 7075	Russell		quant.
titanium 6-4	General Dynamics, San Diego		quant.
titanium 6-4			quant.
aluminum			quant.
Torque loaded sleave	Miller [1]	effect of crack width	qual.
Quench cracked aluminum	Klein [9]	effect of reuse	qual.
Turbine blade cracks	Lomerson [10]	penetrant rating	quant.
Chrome cracked brass	Canadian Air Force [11]	penetrant rating	quant.
Cracked CF-104 ldg. gear	Canadian Air Force	penetrant rating	quant.

[a] qual. = qualitative measure with no numerical analysis, and quant. = quantitative measure of performance.

TABLE 2—*Penetrant parameters* [3].

CDE	SPP	*Kc*	*Q*	*KcQ*
35	31.5	629	33.6	21 100
51	31.6	320	33.6	10 750
54	29.4	55.9	35.3	1 970
63	33.4	700	30.1	21 100
66	28.5	120	35.9	4 300
75	30.4	542	32.7	17 700
76	34.0	3 060	30.3	92 600
80	37.0	7 540	32.9	248 000
89	39.6	11 060	22.4	248 000
91	33.2	1 730	31.9	55 260

NOTE—CDE = crack density efficiency, percent,
SPP = static penetrability parameter, dyne cm^{-1},
Kc = absorption coefficient, and
Q = fluorescent efficiency.

high sensitivity penetrant also ranked lower in static penetrability than another penetrant whose CDE rating was 63 percent.

An evaluation of solvent remover penetrants was performed by the Canadian Aircraft Maintenance Development Unit using chrome cracked panels as well as cracked CF-104 aircraft main landing gear links [*12*]. The landing gear links had extremely tight cracks, as narrow as 10 μin. The relative sensitivity was evaluated by measuring the cumulative length of the defect indications. The standard used was the penetrant system which eventually proved the most sensitive. Cumulative lengths obtained using the other penetrant systems were compared to this standard.

An analysis of the sensitivity of penetrants using the measurement of actual crack length was conducted by Packman et al [*8*] for aluminum and steel cylinders containing fatigue cracks. In this experiment, an assessment was made of the accuracy of the length of the crack indication by penetrants. The length of the defect indication was compared to the length of the actual indication obtained by fracture of the specimen at the completion of the program. There appeared to be no influence of the length of the defect on the length of the defect indication.

In all flaw sizes investigated, from 0.020 to 0.5 in., the aluminum crack indications were about 80 percent of the actual lengths and about 65 percent of actual length for the steel crack indications. Therefore, it appears reasonable that a cumulative crack length measure is related to the penetrant performance. Comparison of the ranking of penetrants using the cracked chrome test panel and the cumulative length procedure showed that the first two penetrant system rankings did not change, and only one penetrant system was interchanged of the five examined [*12*]. Their conclusion was that the chrome cracked panels are satisfactory for the evaluation of penetrant sensitivity.

It should be noted that this conclusion is based on specific inspection procedures and necessarily would not be applicable generally.

A sensitivity test was established as follows [*12*]. Four test panels containing cracked chrome defects, one with coarse defects, one with fine defects, and two with medium defects, were evaluated on each penetrant. During the evaluation, each inspector compared the indications produced by each product with a reference electrographic print showing the size and location of each and all defects. The quality of indications then was ranked on each section of the panel according to an A, B, C, or D rating, with A being all indications present and clearly visible, and D, no indications visible. The reported results showed that the Group VI penetrants could detect fine cracks, while Groups V and IV ranked below the Group VI in some of the ratings. In evaluation of these rankings, it should be recognized that the mirror finish characteristics of the test panels do not test such features as removeability and response of the system when used on more realistically machined finishes.

Fricker [*6*] of the Naval Rework Facility reports a series of tests conducted using cold-rolled steel chrome plated and cracked specimens bent and subsequently straightened to produce lateral cracks ranging from 0.001 to 0.030 in. in width on the center section of the specimen. A machined groove was placed perpendicular to the crack direction to enable side-by-side comparison. Tests also were conducted on titanium strips cracked by a salt water stress corrosion cracking fixture followed by a 800°F soak that produced a wide variety of crack widths. Tests were made to examine the sensitivity of dry, water soluable, and nonaqueous developers. The conclusion was reached that water washable penetrants provide a more reliable inspection process than the postemulsifier types for the new requirements. They indicated that both deep and shallow broad discontinuities are made more visible with greater consistency. One observation reported that the effect of over washing was more pronounced on the titanium specimens than on the steel strips.

Most reported work concerning the influence of dwell time on sensitivity does not differentiate between the dwell mode types, immersion, and drain. Sherwin [2] reviewed the influence of the mode of dwell on the number of indications found in the chrome plated cracked specimens and concludes that a drain dwell is preferable to an immersion dwell, given the same performance characteristics on the same specimen. Flaw indications were easier to see, brighter, and more complete, on specimens examined both with and without developer.

The Ti-6A1-4V stress corrosion cracks produced by stressing with an anhydrous-methanol-sodium chloride (NaCl) solution were examined by postemulsifiable and water washable penetrants in a study reported by Lord and Hollaway [5]. Their study also reported results obtained by inspection of single fatigue cracks in Ti6A1-4V as well as porosity in hand forged billets of Ti6A1-6V-2Sn. The stress corrosion cracks were about 0.0002 in. wide, compared to the fatigue cracks which were about 0.001 in. wide. Visual examination and photographs of the panels exposed to the different penetrants were made to evaluate the effect of dwell time penetrant effectiveness. The results are summarized in Table 3. The results for gross cracks (0.001 in.) agree with Alburger [13] in that all penetrant types were equally as efficient in detection while noticeable differences for the tighter cracks were found for different penetrants and developers.

Borucki [7] reported on the influence of wash times on the decrease in percentage indication brightness as a function of wash times for water washable and postemulsifier, hydrophylic emulsifier spray, lipophic emulsifier (slow and fast action) penetrant systems. In all cases, the brightness indication decreases as a function of increasing wash or emulsification times. The brightness indications were measured on part through fatigue cracked flat test panels similar to those developed for the fracture control demonstration programs.

Several series of penetrant tests have been conducted as part of non-

TABLE 3—*Effect of crack type on developer effectiveness.*

	Developer Type	
Crack Type	Post Emulsifiable Penetrant	Water Washable Penetrant
Gross cracks	nonaqueous wet, dry, and aqueous equally effective no developer	nonaqueous wet, dry, and aqueous equally effective no developer
Porosity	dry nonaqueous wet no developer aqueous	all types equally effective
Tighter cracks	nonaqueous and wet no developer aqueous	nonaqueous wet no developer aqueous

destructive demonstration programs. These programs, while they do not rate penetrants directly, establish a maximum value for the probability of detection of a surface fatigue crack on a flat plate. Tests are run in which a single (or multiple) small surface fatigue crack is place on one side of a machined plate. These plates are mixed with a group of controls, approximately half cracked and half control. They are inspected then by the production inspection groups following carefully developed penetrant inspection procedures. The data are reported in two ways: first as a pass-fail, and second as a probability of detection versus flaw size.

The pass-fail tests are those designed to guarantee that a given penetrant process and inspection team can guarantee that the flaw size chosen for the design analysis can be detected at the required probability with the required degree of confidence. The probability of detection-flaw size curves are constructed to display the actual values of detection for a given penetrant as a function of the surface fatigue crack size.

Several test series have been completed and are reported elsewhere [*14*]. The statistical methods used to analyze and report the data have been reviewed by Packman et al [*15*]. Several penetrant inspections, primarily with Class V and VI penetrants have been completed on aluminum alloys, titanium alloys, and steel, all containing small surface fatigue cracks. In most cases it could be demonstrated that flaws whose surface size was greater than 0.075 in. long by 0.035 in. deep could be detected to at least a 90 percent probability at a 95 percent confidence level.

Two-fold Congruency Method

Lomerson [*10*] developed a test to rate penetrant performance on a quantitative basis which he called the "Two-Fold Congruency" test. The method consists of observing the number of congruent observations obtained on a set of turbine blades processed through three separate runs on the same penetrant. The congruent indication is obtained at the same position on any two runs. The mean number of congruent indications is calculated by averaging the number of congruent indications for each penetrant under investigation. Each blade is inspected three times. The mean number of reproducible indications is given by the average of the total number of observations found on at least two inspections. If an indication is found by one penetrant inspection and not by either of the other two, it is not included in the analysis. The mean number of reproducible inspections is averaged for all of the turbine blades inspected, and the expected variability at a given confidence level is calculated.

The relative sensitivity of the penetrant is calculated by comparing the results obtained on the same set of blades by using the standard penetrant to those obtained using the unknown penetrant. The use of congruencies rather than a total number of indications tends to eliminate occasional random indications from the assessment and, thus, incorporate some measure of the reproducibility into the evaluation process.

Two factors in the quantitative evaluation of penetrants by this procedure should be considered. The sensitivity rating of the penetrant may change if a different group of blades is used as the set of standards. The relative sensitivity of the penetrant is based directly on the ratio of the average number of indications found in a specific set of blades. If all of the indications were washed out, as may be the case using a high resolution water wash penetrant and relatively wide flaws, the results would give a lower number of indications than a less sensitive lipophilic penetrant. The difference would be due to a change in the number and distribution of flaw widths rather than a change in penetrant sensitivity. Since the comparison is made using the same blades which have been cleaned and reinspected, failure of the cleaning process to remove one class of penetrant completely from the defects could modify the second set of results. While extremely long cleaning and vapor degreasing procedures are used to clean the parts, it has been observed that reuse of the components often results in a decrease in the number and intensity of indications.

Lomerson referred to his quantitative procedure as a temporary procedure and ranked 16 penetrant systems, both water washable and post-emulsifier systems, against a penetrant standard. It was pointed up that some penetrants exhibited an extremely large spread in the results, while others showed comparatively small variations. There was no correlation between the sensitivity of the penetrant (compared to the standard penetrant) and the spread in results. All penetrants that ranked above 100 (implying greater sensitivity than the chosen standard) showed scatter values greater than standard penetrant. Then, too, the results of testing operators over a period of time showed some variations. If the same penetrant was selected and compared using different operators, two operators ranked the penetrant system as below 100, while one operator continually ranked the penetrant above 100. A suggested reason for this behavior was the visual capabilities of the operators.

Using the two-fold conguency procedure Hyam [*11*] was able to show the influence of some factors affecting the sensitivity of a penetrant system. His tests included the following.

1. The effect of rinse time on water washable penetrants which showed that increasing the rinse time from 2 to 12 min decreased the sensitivity for two water washable systems examined. Both penetrants had the same sensitivity (related to a standard) at the 2-min rinse time but the water rinse time response was somewhat different.

2. The effect of contact time with a hydrophylic remover system on the sensitivity of two penetrants was shown to be relatively small. The concentration of the hydrophilic remover has a significant influence on the relative sensitivity, in general, the higher the concentration of the hydrophilic remover, the lower the sensitivity rating.

3. The influence of remover contact time using lipophilic removers was shown to be significant. Increasing the time of contact also decreased sensitivity.

4. The effect of developer type on the sensitivity index was shown to be significant; in all cases, the results with no developer were lower than those obtained using a developer. The sensitivity was shown to increase using wet suspension, dry powder, and solvent suspension developers in ascending order.

Reuse of the Specimens

The results of Klein [*9*] indicated that the penetrant blocks may be penetrant inspected, vapor degreased, and reinspected using the *same penetrant* with equivalent results. His specimens were the 2024 aluminum bar stock quench cracked specimens. It was shown that cutting oil applied to a part prior to inspection significantly reduced the effectiveness of the penetrant, even if the part was vapor degreased prior to penetrant inspection. Some reductions in effectiveness are seen, probably due to filling of some of defects with the oil which had not been removed by the degreasing. He further shows that the effectiveness of a penetrant is reduced markedly if the part has been inspected previously with a *different* penetrant, even though the intermediate degreasing has been performed.

The chance that dried penetrant entrapped within a defect due to improper postcleaning could prevent the defect indication from being produced during later inspections is minimized when the same penetrant family, penetrant type, and developer are used. When the same penetrant system is used for subsequent inspections there is no extensive loss in sensitivity, providing proper pre- and postcleaning procedures are used.

However, the response of indications with fluorescent penetrants is reduced significantly when dye penetrants are used for the initial inspection.

The presence of entrapped penetrants due to improper cleaning can reduce significantly the subsequent numbers and brightness of indications. Only the most complete cleaning methods can remove entrapped penetrants effectively. These include acetone cleaning and vapor degreasing. A series of studies conducted by the authors has shown that even with the cracked chrome plates there remains sufficient penetrant within the shallow cracks as to be detrimental. A series of plastic replicas of the penetrant inspected and cleaned plates was made. It was found that there were still fluorescent indications on the replicas after three or four washings and replications, that is, sufficient material remained within the cracks to be strippable by the replica technique. Since the replica method uses acetone cleaning and acetone solvents for making the replicas, one only can conclude that reuse and cleaning of the specimen must be made with extreme care. It has been found that cleaning with dimethylformamide followed by immersion in methyl chloride is an effective cleaning procedure [*16*].

Human Visibility Threshold Influencing Standards

When one considers the degree of reliability that may be possible when using fluorescent penetrant procedures for detection of cracks, one cannot ignore the potential variability that would occur due to differences in visual perception thresholds between inspections. Experiments conducted by Blackwell [*17*] regarding threshold perception of light indications show that the human subject threshold sensitivity varies from session to session. He further discovered that these threshold perception levels can be influenced by a number of variables which generally are thought to be unrelated to visual functions. He concluded that one should not expect threshold data to produce valid indices of visual function.

The important factor presented here is that penetrant indications of defects are not determined necessarily by the visual perception threshold, but depend upon a rather high level of indication of fluorescent or dye indication to indicate the presence of a defect. If the indication is extremely low, the inspector relies upon other subjective judgmental factors to conclude that the indication is a defect. These may include the continuity of the indication, its orientation, the extent of the indication, his knowledge of the history of the part, etc.

ANOVA and Crack Line Intersection Counting

The work of McCauley and Van Winkle [*3*] made use of a measure of the crack line density as a measure of the efficiency of the penetrant. In the following section some work extending that concept is presented.

If a panel containing surface cracks of a wide variety of crack widths is inspected, one normally would expect that a high resolution penetrant system would find a greater number of cracks than a lower resolution system. The low resolution system would be expected to miss some of the finer tighter cracks, while the higher resolution system would not be expected to miss as much. Hence given the *same specimens*, and assuming that there were no changes in the specimen due to the multiple inspections, and that the subsequent inspections results were not modified by the prior penetrant system, one would expect to see a lower crack density for the lower resolution penetrant system.

The problem which arises when many different specimens are used is how to separate out the influence of the true number of cracks in the specimens so that the influence of only the penetrant can be considered. The purpose of analysis of variance (ANOVA) or multiple analysis of variance (MANOVA) is to separate the different levels of the various variables. This enables one to determine if the results are due to different specimens, different penetrants, or simply a random error [*18*].

In this analysis, four specimens with differing crack distributions were used. A typical panel pair is shown in Fig. 1 [*8*]. Six different inspection procedures were used to inspect each panel, these procedures including changes in the penetrant system, dwell time, emulsifier, etc. The specimens were photographed under identical conditions. Four random lines were drawn on each photograph corresponding to each treatment. Thus there were $6 \times 4 = 24$ photographs and each photograph had 4 random lines. For each specimen panel photograph for any treatment line, locations and geometries were kept constant. The number of lines intersection/line were counted and are tabulated in Table 4 as replicates 1 through 4 for each treatment-specimen panel combination. Table 5 also shows row sums (total number of line intersections for all four lines for each treatment-specimen panel combination), column sums (replicate totals), and grand total.

The analysis of variance model assumes that any observation x_{ijk} in Table 4 out of a total of 96 can be written as a sum of population mean, u, replicate effect, α_i, treatment effect, β_j, specimen effect, γ_k, treatment-specimen interaction effect, $\beta\gamma_{jk}$, and chance error, ε_{ijk}.

In other words

$$x_{ijk} = u + \alpha_i + \beta_j + \gamma_k + \beta\gamma_{jk} + \varepsilon_{ijk}$$

The analysis of variance table is computed as follows.

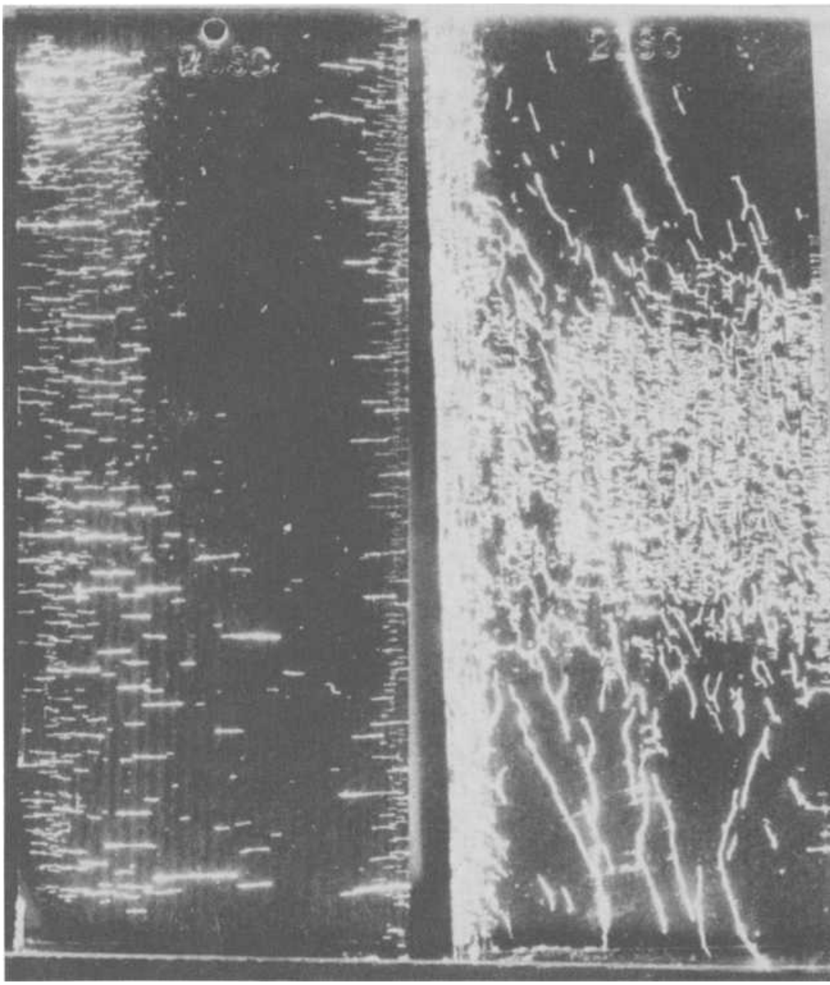

FIG. 1—*Penetrant crack indications on titanium plates after Lloyd and Halloway* [5].

$$\text{correction term} = \frac{(\text{grand total})^2}{\text{total number of observations}}$$

$$= \frac{(4579)^2}{96} = 218408.76$$

$$\text{total sum of squares (SST)} = \Sigma\Sigma\Sigma\, x_{ijk}^{\,2} - (C)$$

TABLE 4—*Penetrant data in a two-way factor with four replicates.*

Factor Treatments	Specimen	Replicate 1 (Line 1)	Replicate 2 (Line 2)	Replicate 3 (Line 3)	Replicate 4 (Line 4)	Total
A	18	43	53	44	50	190
A	19	47	38	120	37	242
A	20	78	57	43	97	275
A	21	67	43	52	51	213
B	18	35	38	24	37	134
B	19	26	30	93	34	183
B	20	61	47	32	68	208
B	21	55	25	27	22	129
C	18	37	47	40	42	166
C	19	39	37	136	48	260
C	20	82	65	60	107	314
C	21	62	46	56	50	214
D	18	24	29	26	21	100
D	19	21	39	96	33	189
D	20	76	63	52	100	291
D	21	54	29	47	43	173
E	18	24	32	29	21	106
E	19	22	31	7	1	61
E	20	65	53	39	62	219
E	21	62	31	32	32	157
F	18	35	40	37	41	153
F	19	38	34	14	75	161
F	20	63	48	46	87	244
F	21	67	41	47	42	197
		1183	996	1199	1201	7579

$$\text{SS (replicates)} = \frac{(\sum_j \sum_k x_{ijk})^2}{n_j n_k} - (C)$$

$$\text{SS (treatments)} = \frac{(\sum_i \sum_k x_{ijk})^2}{n_j n_k} - (C)$$

$$\text{SS (specimens)} = \frac{(\sum_i \sum_k x_{ijk})^2}{n_i n_k} - (C)$$

where

n_i = number of replicates,
n_j = number of treatments (inspection procedures),
n_k = number of specimen panels,
$n_i n_j n_k - 1$ = total degrees of freedom,

$$n_i - 1 = \text{replicates degrees of freedom,}$$
$$n_j - 1 = \text{treatment degrees of freedom,}$$
$$n_k - 1 = \text{specimen degrees of freedom, and}$$
$$(n_j - 1)(n_j n_k - 1) = \text{error degrees of freedom.}$$

Mean sum of squares (MSS) is obtained by dividing SS by corresponding degrees of freedom.

$$F \text{ ratio} = \frac{\text{MSS}}{\text{error MSS}}$$

If F ratio is greater than $F_{\gamma_1\gamma_2\alpha}$ we conclude that there is significant effect due to that factor where γ_1 and γ_2 are degrees of freedom for the numerator and denominator, respectively, and α is level of significance. The value $(1 - \alpha)$ is the confidence. All the calculated values are shown in Table 5 alone with F values from calculated statistical tables for 95 and 99 percent confidence levels.

From Table 5 the following can be concluded.

1. There are no significant replication effects at both 95 and 99 percent confidence levels. This means that replicates were not very much different. Hence the number of crack distributions in each plate was essentially uniform.

2. The type of penetrant inspection procedure (treatments) had *significant* effect on detection of cracks at both 95 and 99 percent confidence levels.

3. Type of specimen panel also had a significant effect on detection of cracks at both 95 and 99 percent confidence levels. This means that different specimens were different as to the number of surface flaw distributions.

4. There is no significant interaction between type of specimen panel and type of inspection procedure effect at both 95 and 99 percent confidence levels. This is important since the specimen panels had significantly different number of flaw distributions and still the type of penetrant inspection procedure did not react differently for different types of specimen panels flaw distribution, that is, a good inspection procedure was good for any type of flaw distribution.

Although the ANOVA technique is able to differentiate between the effects caused by the differing specimen defect distributions and show that there is a difference in penetrants, one would not be satisfied to use these specimens as a standard. To this end, a group of large cold rolled steel plates were chrome plated and cracked in four-point bending to produce a series of parallel cracks in the central portion of the plate. Replicas taken from the surface of the plates indicate that the crack line density is given by 1.202 cracks/mm with a standard deviation of 0.97

TABLE 5—*Analysis of variance table (including analysis of interaction effects).*

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Sum of Squares	Calculated F Ratio	Theoretical at Confidence, %	
					95	99
Replication	3	1237.365	412.455	0.99	2.75	4.09
Main effects						
type of treatment A, B, C, or D, etc.	5	7598.4275	1519.6855	3.6494	2.36	3.30
type of specimen 18, 19, 20, or 21	3	10779.0317	3593.010567	8.6282	2.75	4.09
Interaction effect	15	3746.0308	249.73	0.5997	1.82	2.32
Error	69	28733.385	416.4259			
Total	95	52094.29				

cracks/mm. The use of the penetrants on these plates produced indications as shown in Fig. 2. Crack line intersections were made by counting the number of times a line parallel to the longitudinal axis intersected with the indications of the defect on a photograph. When two different Class V penetrants were examined the results were

Penetrant A	0.91 cracks/mm, standard deviation 0.04 cracks/mm
Penetrant B	1.26 cracks/mm, standard deviation 0.04 cracks/mm

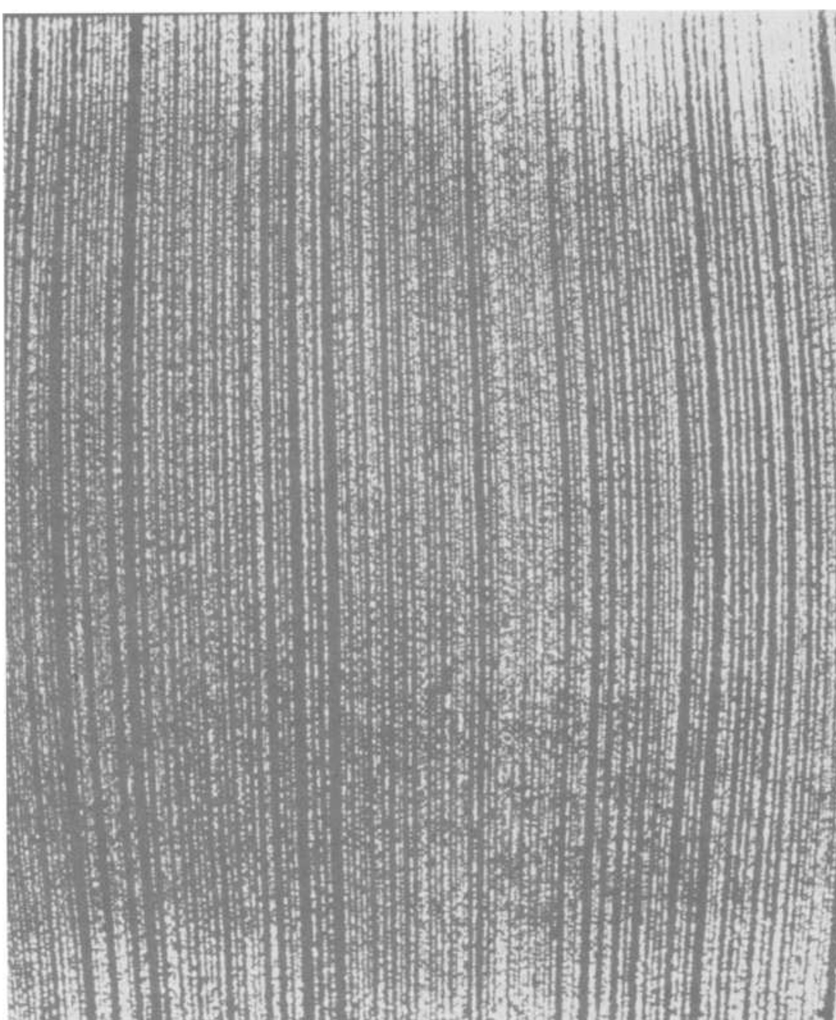

FIG. 2—*Penetrant indications on chrome plated cracked steel plates. Width of plate is 4 in.*

Thus it appears that Penetrant B is detecting more cracks per millimetre than Penetrant A. The major difficulty in use of this type of a specimen as a standard is due to the variability in actual crack density even though all procedures used to make the specimen are identical. The standard deviation of the plates is greater than that shown by the penetrants. If the variations from plate to plate are significant, it could lead to erroneous rankings and must be accounted for by the use of the analysis of variance procedures outlined previously.

Acknowledgments

The authors wish to acknowledge the support of the Air Force Materials Laboratory under Air Force Contract No F-33615-76-R-5166. The initial portions of this program were supported under a grant from the Air Force Office of Scientific Research under the direction of William Walker.

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Magnetic Flux Density Measurements Relative to Magnetic Particle Testing

REFERENCE: Schroeder, K. W., "**Magnetic Flux Density Measurements Relative to Magnetic Particle Testing,**" *Nondestructive Testing Standards—A Review, ASTM STP 624,* Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 211-219.

ABSTRACT: The basic magnetizing requirements relative to magnetic particle testing are reviewed briefly and flux density (B) is established as the all important factor. Rules of thumb and various magnetic field measuring techniques are discussed relative to their usefulness in determining magnetizing levels. It points up the limited nature of field measuring techniques and classifies them as laboratory tools.

KEY WORDS: nondestructive tests, standards, magnetic particle tests, flux density

The magnetic particle method is based on the premise that magnetic discontinuities in a magnetized part will cause localized magnetic leakage fields to occur at the surface of a part. When these leakage fields are of sufficient strength to attract and hold finely divided magnetic particles, an indication can be formed which discloses the location and general extent of the discontinuity. A problem arises when one is confronted with the task of determining that the level of magnetization within a part is of ample magnitude for such testing purposes.

Various guides and techniques currently are being utilized throughout the industry in an effort to assure that adequate levels of magnetization are being achieved. These guides and techniques are discussed in the text that follows with the intent of providing some insight relative to their effectiveness in providing useful information as well as their shortcomings.

Magnetic Field

It might be well to define briefly the basic differences between magnetic

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field intensity, H, and magnetic flux density, B; H represents the magnetizing source and B, the resultant degree of magnetization. The two terms are related by the familar equation $B = \mu H$ where μ is the effective permeability. While there are numerous units associated with these terms, B quite commonly is expressed in gauss (G) or kilogauss (kG) and H in oersteds. In air, where the relative permeability is equal to one, the numerical values for gauss and oersted are identical. Hence, the measurement of either B or H automatically gives the value of the other. However, this is not the case when ferromagnetic material is involved.

For purposes of magnetic particle inspection, the value of B is the all important factor. The value of B within a part must be driven above some minimum value by the application of a suitable magnetizing force, H, in order to develop indications of magnetic discontinuities. This minimum value of B will vary in accordance with the variations in magnetic properties displayed by the different engineering grade materials normally encountered in the field of nondestructive testing (NDT). Magnetization curves are not readily available for these materials, and even if they were, their usefulness would be limited.

There is quite a bit of latitude relative to the value of B that will produce a useable indication. Obviously, the intensity of the resulting indication will tend to increase as B increases, but it is a gradual phenomenon rather than abrupt. With reference to Fig. 1 which depicts a typical B-H

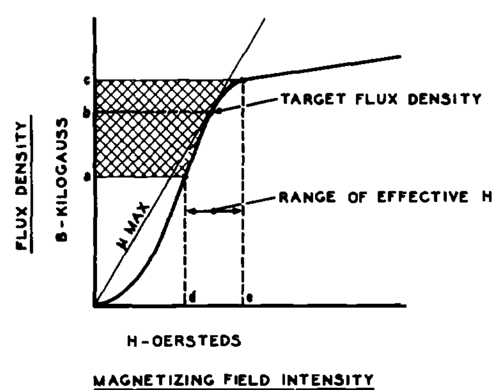

FIG. 1—*Typical* B-H *curve.*

curve, it can be seen that a variation in B from Points a to c corresponds to a variation in H from Points d to e. Point b in Fig. 1 represents what might be regarded as the ideal level of magnetization for magnetic particle inspection. It lies just below the knee of the curve and, consequently, should be attainable with reasonable values of H. The shaded area between Points a and c represents a range of B that will provide an adequate level for inspection purposes. Higher values of B can be achieved with the application of increased values of H but at a reduced rate of effectiveness.

Excessively high values of B (approaching saturation) are detrimental since they usually are accompanied by strong extraneous leakage fields that either mask or impede the formation of indications. Conversely, excessively weak fields do not produce the desired results since potential leakage fields due to a discontinuity are diverted inwardly to follow a path of least reluctance in the magnetic material.

Rules of Thumb

In the absence of any absolute means of determining the ideal magnetizing force required for a specific part, rules of thumb were established and have been used throughout industry for many years. They have served as a valuable guide for arriving at reasonable magnetizing force levels in accordance with the geometric variations encountered from part to part. Emphasis should be placed on the term *guide* since this is the only intent. These rules of thumb are discussed in the following sections.

Circular Magnetization

When a part is to be magnetized circularly by the direct passage of current through it or through a centrally located conductor, the following rule of thumb applies: 1000 A/in. of part diameter. This value of current produces a value of H equal to 158 oersteds at the outer surface of the part. As far as most engineering materials are concerned, this is a very conservative value of H in that it will result in a value of B that may be somewhat higher than ideal. In actual practice, it very well might be necessary to use a lower value of magnetizing current to eliminate indications of flow lines and other background contributing factors that tend to mask pertinent indications.

The rule is applied easily and with proven results on small to medium size parts, which was probably the intended area of application. However, on large diameter parts, it can result in some exceedingly high amperages that defy existing power pack capabilities.

Coil Magnetization

There are several rules of thumb pertaining to coil magnetization, but the most common one is for small parts placed on the bottom (inside diameter) of a coil and occupying less than 10 percent of the coil area. The ampere-turn requirements are given by

$$NI = \frac{45\,000}{L/D}$$

where

N = turns in magnetization coil,
I = magnetizing current in amperes,
L = length of part, and
D = diameter of part.

This takes into account the demagnetizing effect that is a function of the L/D ratio and is illustrated in Fig. 2.

As a part becomes magnetized longitudinally, it develops North and South poles like any bar magnet. Also like any bar magnet, it has its own

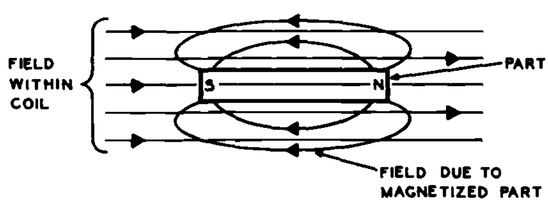

FIG. 2—*Demagnetizing effect of part being magnetized in a longitudinal field.*

leakage field pattern with the lines of flux leaving the North pole and returning to the South pole. As indicated in Fig. 2, this field opposes the applied coil field and detracts from the magnetizing effect of the applied field.

This rule of thumb was developed empirically from laboratory test data. Within certain limits, the resulting ampere turns will produce a flux density within the specimen of 70 000 lines/in.^{2} (10.85 kG). Experience has indicated that a flux density of 70 000 lines/in.^{2} is of sufficient magnitude to permit inspection to be carried out on aircraft quality parts.

The rule is applied easily, and with good results, to simple cylindrically shaped parts. However, when parts become quite complex, determining what actually constitutes the L/D ratio can cause confusion.

Measurement Techniques

The need to determine the adequacy of a magnetic field within a specimen has brought the use of a variety of approaches. These include fluxmeters, Hall effect instruments, artificial crack indicators, and eddy current instruments. Their modes of operation and effectiveness are discussed individually in the text that follows.

Fluxmeter (Ballistic Galvanometer Type)

This instrument requires that a small search coil be wound around the area where a measurement is to be made. The resultant readings correspond to changes in flux linkages within the search coil as the direct current magnetizing source is varied in magnitude. Thus it indicates flux density within that portion of the part enclosed by the search coil as a function of magnetizing force (B versus H). When applicable, this method does have the advantage of not requiring the part to be altered in any way that would change the magnetic flux distribution. The magnetizing source employed should be adjustable and have provisions for conveniently reversing the polarity of the applied magnetic field.

The flux density within relatively large parts can be explored by utilizing a slightly modified technique. Two appropriate through holes can be utilized for winding a search coil in a given area. The area between the holes and enclosed by the search coil windings becomes the test area. The presence of the holes does distort the magnetic field distribution. Hence, the size of these holes usually is kept as small as practical in order to minimize the distortion.

The validity of the information desired from measurements with instruments of this type is dependent upon the equal distribution of magnetic flux across the area enclosed by the search coil. The instrument integrates the voltages generated in the search coil due to changes in flux linkages. Increasing flux linkages result in a meter deflection in one direction while decreasing flux linkages result in a deflection in the opposite direction.

The divisions of deflection provide a basis for computing the flux density when coupled with the number of search coil turns, the cross-sectional area enclosed by the search coil, and the instrument sensitivity constant. A typical setup and procedure is shown in Fig. 3.

Since the change in flux lines across the entire cross-sectional area enclosed by the search coil contribute to the meter deflection, the resultant calculated flux density is of little value unless it reasonably can be assumed that the flux lines are distributed equally across the area and are of the same polarity. This requires that consideration be given to the magnetizing method and its application relative to the area in question with respect to spacing, cross-sectional area, etc.. The magnetizing current itself must be a nonpulsating direct current in order to minimize inductive reaction or skin effect which would not be conducive to equal distribution. It might be noted also that the meter movement itself is only compatible with a nonoscillating or direct-current type field.

Hall Effect Instruments

The heart of any Hall effect instrument is the probe which contains an

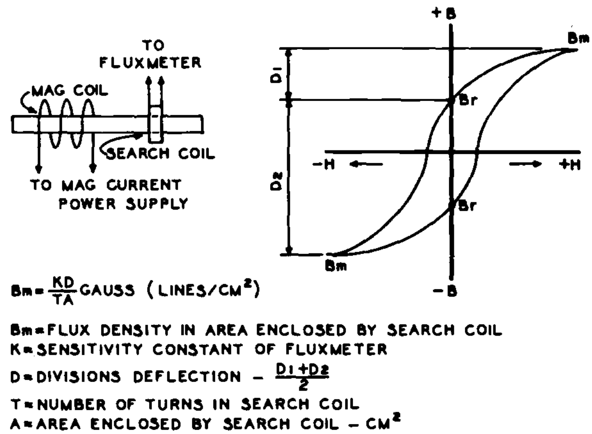

FIG. 3—*Typical setup and procedure for taking fluxmeter readings.*

element having very special characteristics. When a magnetic field is applied perpendicular to its surface, a signal voltage is developed across what normally would be equal potential points on the current carrying element. The magnitude of this signal voltage is proportional to the flux density of the applied field integrated across the entire area of the element.

These special probes in conjunction with the proper instrumentation can be quite useful for measuring the flux density in air gaps and external leakage fields emanating from magnetized parts. However, they are not applicable when it comes to measuring the fields contained within a part. Readings of this nature would require that some sort of opening be introduced into the part for probe insertion. Such an opening distorts the internal magnetic field, and the usefulness of any reading would be questionable.

Small probes can be utilized to measure the tangential magnetic field intensity, *Ht*, at the surface of a part being magnetized. Such values of *Ht* are useful for laboratory type investigation where previous work has been performed to establish the relationship between *Ht* and *B* in the form of a magnetization or *B-H* curve. In the absence of such previous history on a part or material, or both, there is no way of relating *Ht* to *B* within the part. However, measurements of *Ht* can be a valuable laboratory type tool when used with proper discretion.

Artificial Crack Indicator

Various devices have been designed and used in industry for the purported purpose of indicating when a part is magnetized sufficiently for magnetic particle inspection. All of these devices contain artificially created magnetic discontinuities that result in a magnetic particle indication when subjected to an appropriate magnetic field. In use, they are placed on the surface of a part that is being subjected to a magnetizing force, and the buildup of an indication on the device is supposed to be indicative of an adequate magnetizing current level for inspection.

Figure 4 depicts three of these devices for illustrative purpose. Devices A and B are quite common in industry while Device C has not appeared in the field; it was included because of its significantly different characteristics. All three respond to the *Ht* at the surface of a part but at different levels of sensitivity. When individually placed in the center of a 12-in.-diameter magnetizing coil and the wet method employed, the applied magnetic field required to develop reasonably good indications is of the following order of magnitude.

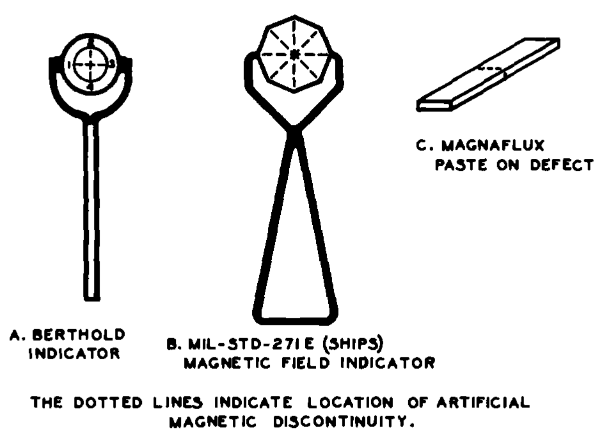

FIG. 4—*Examples of artificial crack indicators. The dotted lines indicate location of artificial magnetic discontinuity. (Device B is according to the Military Standard on Nondestructive Testing Requirements for Metals (MIL-STD-271E (NAVSHIPS)).*

Device	H, oersteds	Coil Field, A-Turns
A	48	1125
B	80	2000
C	185	4000

The values of H required for the disclosure of the artificial discontinuity indicate substantially different degrees of sensitivity for the three devices. Results of a similar nature could be expected if the circular method had been employed as the magnetizing source.

These devices, and any of a similar nature, respond to *Ht* at the surface of a part in much the same manner as a Hall probe. They are similarly a laboratory type tool but necessarily do not relate to the level of *B* within a part. Unlike a Hall probe that results in a discrete numerical reading, use of these devices require the operator to judge when an indication is indeed an indication. Bath application and drainage are also left to his discretion.

Eddy Current Instruments

Variations in the magnetic properties of a material generally have a distinct influence on an eddy current response. This is not unusual since the generation of eddy currents is basically an electromagnetic phenomenon. There are a few probe-type eddy current instruments that show some promise of being used to indicate when the magnetic field within a part is suitable for developing magnetic particle indications. Laboratory tests tend to indicate a definite response to changes in permeability (μ), but surface conditions such as scale or work hardening and the magnetic state of the part also have a significant influence on the results. To date, meaningful results only can be achieved by first developing a calibration curve for each particular material and then carefully controlling the other influencing factors. Additional development work is a definite requirement before this approach can be classified other than a laboratory curiosity.

Summary

The rules of thumb, in general, provide a good basis for establishing adequate levels of magnetization, but they too have limitations and are subject to different interpretations when the part deviates from a simple cylindrical shape. They also are not applicable when special techniques, such as the induced current method, are being employed.

Each of the magnetic field measuring techniques discussed fall far short of qualifying as a universal means for determining the flux density within a part under test. Only one, the fluxmeter method, responds directly to *B* within a part, and its application is restricted very much due to inherent limitations. The Hall instruments and artificial crack indicator techniques both respond to *Ht* adjacent to the surface of the part and consequently can not be related readily to the all important *B* within the part. The artificial crack indicator presents additional problems such as variations in sensitivity and their susceptability to erroneous results due to extraneous leakage or applied fields.

It becomes apparent that the magnetic field measuring techniques available are of a very limited nature relative to magnetic particle testing. Those that are available must be classified as laboratory type tools, and, as such, must be used with considerable discretion.

G. T. Yonemura[1]

Considerations and Standards for Visual Inspection Techniques

REFERENCE: Yonemura, G. T., "**Considerations and Standards for Visual Inspection Techniques,**" *Nondestructive Testing Standards—A Review, ASTM STP 624*, Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 220–230.

ABSTRACT: When we look at the capacity of the human visual system we see that man can adjust to a wide variety of operating conditions. But, unless we have detailed information of the conditions for which these processes are to be standardized and quantitative descriptions of the tasks to be performed, the advantages to be obtained by visual science applications cannot be utilized optimally. The modulation transfer function would be an image evaluation technique applicable to nondestructive testing (NDT). Standardized tests to assess day-to-day performance as well as initial capacities should be developed. These tests should be derived from visual capacities correlated with the tasks to be performed.

KEY WORDS: nondestructive tests, standards, visual inspection

In assessing the acceptability of mensurative techniques, two basic uncertainty (reliability) measures are involved: the repeatability of measurements with a given instrument and the agreement between different instruments or installations. Similar performance assessments leading to consistent performance should be required of visual techniques in nondestructive testing (NDT). One indication of this need may be the results of the Air Force interlaboratory test involving eleven installations as reported by Gulley [*1*].[2] The percentage of defects detected ran from a high of 93 to a low of 19 percent.

Information Requirements

The performance of human observers in NDT (involving visual inspection) can be separated into two broad categories. The first involves de-

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[2] The italic numbers in brackets refer to the list of references appended to this paper.

tecting the inhomogeneity that may or may not be a defect. The second involves the interpretation of the inhomogeneity as being a fault or some artifact. To a large extent, detection can be said to be dependent upon the physiological attributes of the observer, and decision making or interpretation can be said to be, for the most part, a function of the cognition and experience of the observer. This dichotomy between physiological and cognitive attributes is not clear cut, as there are contributions of both to detection and interpretation.

In this presentation we will be discussing only the first problem—detection. Furthermore, we will be interested primarily in the problem of consistency of detection for the more difficult tasks. The fundamental measure is the probability of detection, detecting an inhomogeneity that may or may not be a defect. I would like to digress for a moment to describe the basic stimulus configuration used in most of the experiments, the results of which will be used to illustrate visual phenomena of interest to visual nondestructive inspection (NDI). In Fig. 1, *a* is the target to be

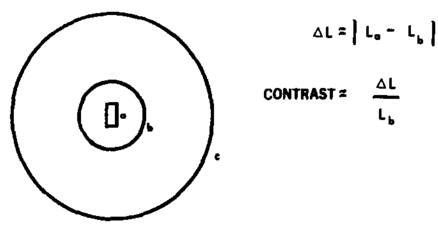

FIG. 1—*Paradigm of stimulus configuration used to investigate contrast;* (a) *target,* (b) *background, and* (c) *surround.*

detected seen against a background, *b, c* being the area surrounding the task. ΔL is the absolute value of the difference between the luminance of the target and its background. Contrast is defined as ΔL divided by the background luminance. In all of the experimental data shown, no attempt will be made to describe the stimulus parameters precisely. The purpose of these data is only to indicate the shape of the function.

Measures of Uncertainty

Within Observers

As in any instrumental measurement technique, our first concern is the consistency or repeatability of measurements with a given instrument. This concern should hold also for the human eye. Will the same inspector be able to detect targets of the same difficulty equally often on different days? Figure 2 shows the results from a highly experienced observer obtained on two different days. The stimulus parameters were the same, the

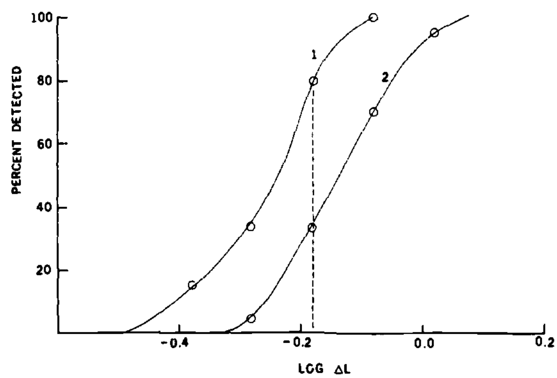

FIG. 2—*Individual variation from day to day (adapted from Ref* 2).

only observable difference being that the two curves were obtained 24 h apart. Note that on Day 1, this subject detected the target 80 percent of the time when there was a −0.18-log unit difference in the luminance between the target and background. On Day 2, a −0.18-log unit difference was detected only 35 percent of the time. Also note that the variability in the response of this observer is about the same for Days 1 and 2, as indicated by the similarity in the slope of the two ogives. It has been the author's experience that data taken 1 or 2 h apart are very similar and do not manifest the changes that may occur over a 24-h period. This type of performance typically is obtained from experienced observers in visual psychophysical experiments. An inexperienced observer will display a larger separation between the ogives, the separation decreasing with increases in experience. We see that even experienced observers display variability in visual capacities that may vary from day to day. This indicates the need for a test that the inspector can use to calibrate himself, that is, "calibrate," in the sense that he can determine whether he is performing at a prescribed performance level or better at that time. Further, he will not be ready to perform critical visual inspections unless he can detect a target of predetermined size, contrast, luminance, and blur. Later we will discuss some variables that influence detection capacity, and by following prescribed procedures, the inspector may be able to bring his performance to the required level. Of course, these criteria assume that the inspector has displayed a minimum visual sensory capacity as tested in NDI by physical examinations involving acuity tests.

Between Observers

No matter how consistent an inspector may be in repeating his performance day after day, unless his performance meets some minimum specified performance level his performance is unacceptable. An analogy in instrumental measurement will be interlaboratory tests conducted to assess consistency of measurements between laboratories and instruments. A given instrument in a given laboratory may give high repeatability time after time, but its measurements may be inconsistent with those from other laboratories. This second source of inconsistency, in visual inspection techniques, is the variability *between* observers. In Fig. 3 we see the

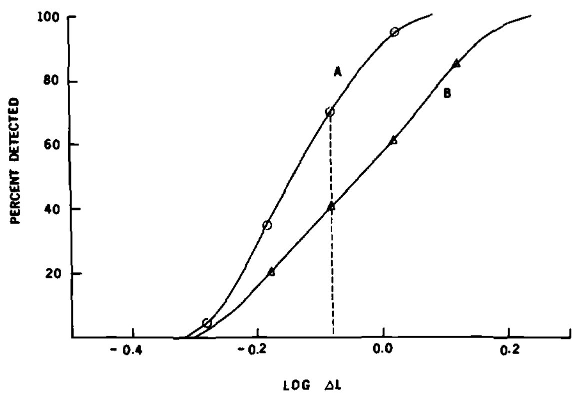

FIG. 3—*Variations between individuals (adapted from Ref 2).*

results for two different subjects obtained under identical conditions. One observer detects a −0.08-log unit difference 75 percent of the time, whereas another subject can only detect this same difference 40 percent of the time. As stated earlier, an appreciation of the need for standardizing this performance is indicated in NDI by the physical examinations involving acuity tests. An important question is: are we using the correct physical correlate to assess this performance?

Between Groups of Observers

Within and between observers inconsistency can be minimized by using more observers. Figure 4 presents the results from an experiment where the performance of the group as a whole is presented, that is to say, at least one member of the group detected the target. For a single observer, the probability of detection for a luminance level of 1.7-log luminance unit is about 10 percent. When we double the number of observers where now the probability of detection is based on at least one of two observers detecting the target, the percent detected increases to about 30 percent. With five observers the percent detected increases to 65 percent. We can bring percent detected to the 95 percent level by using ten observers. There is another important fact that this set of curves tells us. As the number of observers are increased, the slope of the ogives becomes steeper.

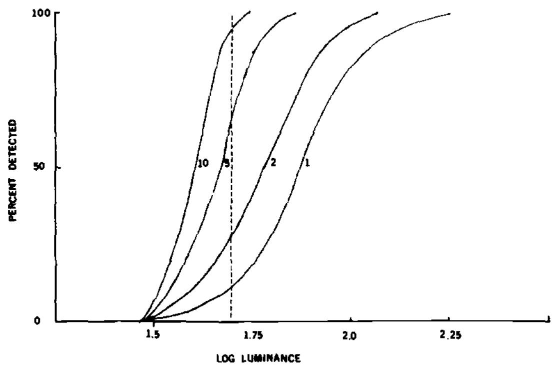

FIG. 4—*Target detection probability by groups composed of 1, 2, 5, and 10 observers (adapted from Ref 2).*

Since the slope of the ogive is a measure of the standard deviation or the variability of the data, we also can state that as the number of observers are increased, the consistency of the data increases.

The writer fully realizes the impracticality of using ten observers to inspect the same specimen. These data were presented to give some indication of how consistency can be improved.

Stimulus Parameters

Luminance Range

We saw that in standardizing the visual performance of nondestructive inspectors, we must consider within observers, between observers, and between groups of observers' inconsistencies. The aim is to obtain as consistent a performance as possible using the human observer as the detector. The human visual system is a highly adaptive one. In Fig. 5 we see that the eye, under the most optimum conditions, can see a spot of light less than 10^{-5} cd/m^2. The upper limit of visual tolerance or the pain threshold is about 10^5 cd/m^2. The low to high range covers ten orders of magnitude or a ratio of 10 billion to 1. This large sensitivity range of the eye should not be construed as indicating that the eye is not sensitive to small changes. The eye can detect luminance changes as small as 1 percent.

Light and Dark Adaptation

What are some of the physical variables that may lead to inconsistencies in responding? I would like to state here that the variables to be discussed do not necessarily apply equally to the different nondestructive testing

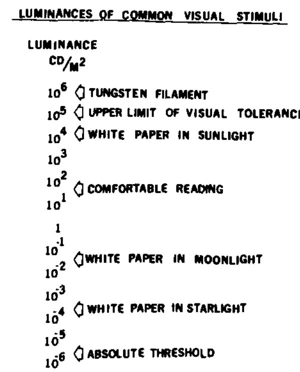

FIG. 5—*Luminance levels of typical visual stimuli* (*adapted from Ref* 3).

methods. A variable may be important for one technique but have little effect on another. For example, dark adaptation may be an important variable in X-radiography, but may be of less importance to liquid penetrant techniques. Figure 6 gives the luminance level required to detect a spot of light against a dark background as a function of dark adaptation or time in the dark. The parameter is light adaptation or the luminance level to which the eye was adapted for 5 s previous to being dark adapted. It is obvious that after 5 min in the dark, the sensitivity of the eye still is affected differentially by the luminance level of the preadapting light. Even after 10 min, the luminance level required to see the spot of light after preadapting to a photoflash is significantly greater than that required for the other light levels. For critical or more difficult tasks, the eye must be adapted for a longer period of time. For example, if the inspector just stepped in from the outdoors on a sunny day, he would be significantly less sensitive to the inspection task as opposed to having been in a dimly illuminated waiting room, before performing the inspection.

We obtain similar results by varying light adaptation duration rather than luminance levels of the adapting light. Figure 7 is similar to Fig. 6, but in this case the adapting light luminance was kept constant at 1060 cd/m^2 and the light adaptation period varied. We see that even after 10 min of dark adaptation, the luminance required to see a spot of light is affected significantly by the length of time the observer was light adapted prior to dark adaptation. For critical tasks, even leaving the radiography room for 10 min to go to the rest room may significantly affect the ability to detect a hairline crack since the dark adapted state is unadapted quickly when the eye is exposed to light. The purpose of presenting these graphs is not only to describe the phenomena, but to indicate that in many cases we may have the quantitative data, the need being to determine the stimulus levels encountered in NDT.

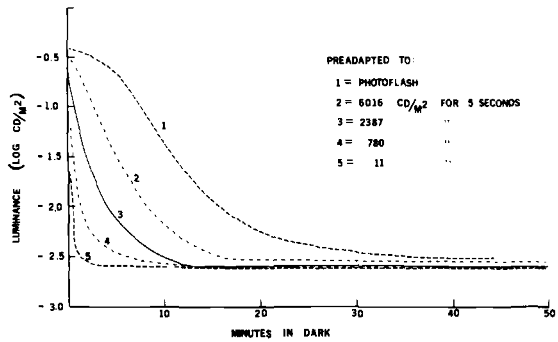

FIG. 6—*Dark adaptation threshold following short exposures high luminances (adapted from Ref* 4).

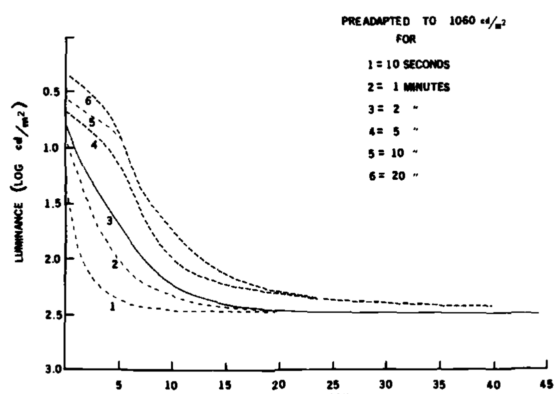

FIG. 7—*Dark adaptation thresholds following exposures to a luminance of 1060 cd/m*[2] *of different durations (adapted from Ref* 4).

Luminance Level

Figure 8 indicates that when working at threshold levels, target detection can be improved by increasing the luminance level. For example, a target with log contrast of -0.5 cannot be detected at -1.0 log cd/m^2 but will be detected by increasing luminance level to 1.0 log cd/m^2. These data only hold for a target of specific size, in this case one subtending 40 min of arc. A word of precaution: these values are for targets that barely can be detected. For targets with high contrast, such that they are easily observable, luminances above an optimum level may decrease the contrast or the "goodness" of the target.

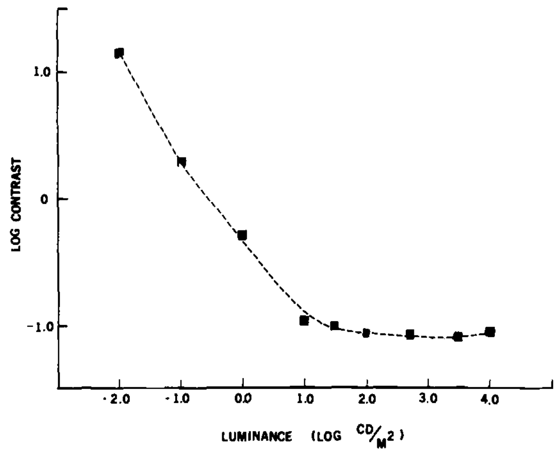

FIG. 8—*Luminance contrast threshold as a function of background luminance (adapted from Ref 2).*

Target Size

Figure 9 shows the obvious: as the size of the target is increased, the luminance required to see a spot of light decreases. For NDI we will probably be more interested in the ability to detect targets with different contrast levels. Figure 10 indicates that as the target diameter decreases, contrast must be increased in order to detect the target. Note that in NDT we will be dealing with the smaller-sized targets, where there appears to be a linear relationship between angular subtense and log contrast.

These will be some of the variables that must be considered in standardizing the performance of NDT inspectors or at the least to optimize con-

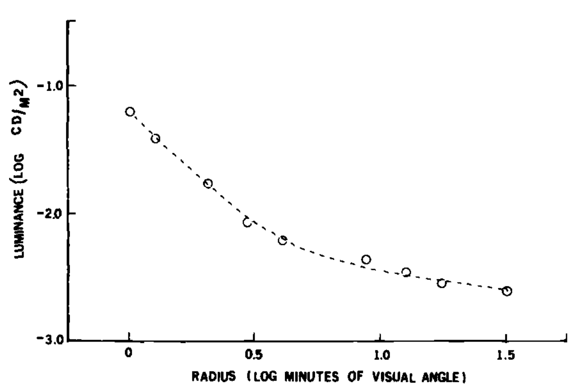

FIG. 9—*Threshold luminance as a function of radius of a circular target (adapted from Ref 5).*

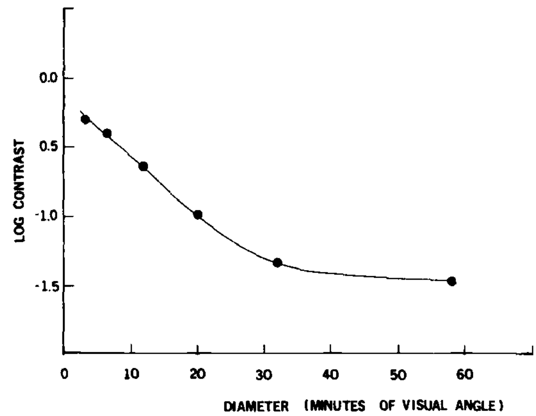

FIG. 10—*Contrast threshold as a function of the diameter of the test field (adapted from Ref 6).*

sistency of performance for a given inspector, performance between different inspectors, and performance between groups of inspectors.

Standards for Visual Inspection Techniques

Data Required

Several difficulties arise when we attempt to apply the data on the capacity of the human visual system to NDI techniques. When we looked at some examples of the capacity of the visual system we saw that it had a large responding range depending on the circumstances under which it was used. In fact, the data in any sensory field are data that describe how a given capacity is dependent on any one of a large number of variables. Any discussion on standardizing the sensory capacity of the human eye must be based on the circumstances under which this capacity is to be utilized. We must know what the eye is expected to see and the conditions under which the discriminations are to be made. We know considerably less of the demands made on the visual system by NDI than we do of the limitations of the human eye. This deficiency is a serious one. We need quantitative measures describing the physical correlates of what the eye is expected to detect. For example, in radiography dimensional descriptions of the defect measured on the material has limited value in visual standards for NDI. The eye is asked to look at the radiograph, consequently the physical measure of interest is the defect as displayed on the film, irregardless of how much it may differ from the actual defect. What is required are microdensitometric scanning measures of the defect taken directly from the radiograph. An analogous argument applies to liquid penetrants and magnetic particle inspections. Microphotometric scanning measures of the fluorescent indications will provide the necessary physical correlates required to describe completely the fluorescent indications as seen by the eye. Only then can we determine the capacity demanded of the eye and formulate meaningful standards leading to a more consistent defect detection probability within and between observers as well as between installations.

Modulation Transfer Function

There does not seem to be much doubt that the primary visual parameters correlated with NDT visual inspection tasks are contrast, size, luminance, and blur. The question remaining is the magnitude of these parameters in NDI as discussed earlier. Time in almost all instances can be treated as infinite, as far as task description is concerned. The variables just listed are treated systematically by the concept of modulation transfer function (MTF). We recommend that this concept be used in formulating NDI standards. An advantage is that the technique is being utilized currently in optical evaluations, and many of the techniques developed can be transferred directly to NDI. The MTF is being used already in medical radiography and also is being utilized in NDT for image enhancement techniques. The net effect of two variables can be treated as the product of the two variables on modulation, that is, contrast. In the speakers opinion, the ability of MTF to handle blur, an area which has been neglected in most applied visual problems, is in itself sufficient reason for using MTF.

Recommendations

In summarizing, I wish to suggest that the primary need is to collect quantitative data describing the stimuli that the eye has to detect. These data preferably should be in the form of microscanning which can be translated into MTF. The MTF of critical faults can serve as the minimum acceptable limits of detection capacity required from an observer or installation. These critical capacity requirements will form the basis from which standardized tests should be developed.

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F. T. Farrace[1]

Standardization of an Automatic Inspection System

REFERENCE: Farrace, F. T., "**Standardization of an Automatic Inspection System,**" *Nondestructive Testing Standards—A Review, ASTM STP 624,* Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 231-245.

ABSTRACT: Laser surface inspection of continuous web materials is capable of more objective results than most human inspectors. This fact complicates the standardization and calibration of the laser system. Calibration methods are discussed, including the human operator himself, resolution grids, and other transfer standards.

KEY WORDS: nondestructive tests, standards, inspection, surface inspection, lasers, continuous web processes, calibration

As costs increase, both in raw materials and manufacturing processes, more and more attention is devoted to the role of on-line visual inspection as a potential source of savings. This interest is justified entirely, for if on-line visual inspection were feasible at contemporary production speeds, great savings could be realized in many applications in metals, paper, and plastics manufacture.

For example, if a coil of sheet steel that contains visible defects is not diverted at the pickle line but continues instead through the temper mill before the defects are discovered, as much as $5 000 might be lost.

Similarly, a 10 000-lb roll of painted sheet aluminum that must be scrapped because of defects in the painting may carry with it a price tag of $10 000.

A 10-ft sheet of raw paper for laminate, if rejected by visual inspection prior to processing, might cost only $1.50. After lamination and treatment, however, the rejection of the completed sheet of laminate at the finish line might result in $15.00 lost.

Where the prospective defects in the material consist of visible blemishes, visual inspection would appear to be the preferred technique for

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detecting them. And, indeed, in many applications, the material is sampled and inspected visually—a process that detects some portion of the defects at the expense of considerable handling.

In many industrial processes, materials are carried along on a moving web at speeds well in excess of 100 ft/min, frequently at speeds of 500 or 600 ft/min, and even at speeds as high as 2000 ft/min. A dirt spot 1 mm in diameter moving at 2 or 3 m/s is, of course, extremely difficult for a human inspector to see, especially if the spot is a rare and unpredictable event that may occur at any location across a 160-in.-wide web.

To expect human inspector reliably to detect 100 percent of such defects on a continuous, full-shift basis, day after day, is to set an extremely high standard for performance that is probably not achievable, even in principle. Yet, in numerous applications in the metals, plastics, and paper industries, such visual inspection clearly would pay big economic dividends—if it could be achieved.

The design of automatic inspection equipment to perform such tasks, therefore, has attracted considerable interest in recent years and a number of devices and techniques have been developed.[2-5]

Principles of Operation

Whatever optical, electronics, or mechanical inspection means, or a combination thereof, are adopted, there remains the need to standardize and calibrate equipment. Traditionally, where visual inspection is used, the standards against which materials are judged are developed for interpretation by humans. Usually they consist of samples of photographs or drawings, or of verbal descriptions that specify what the blemishes "look like."

An automatic inspection system, however, operating without human perceptions, must rely on electrical signals produced by various transducers and on programmed interpretations of those signals. Where visible flaws are to be detected, the transducers most commonly chosen are light sensitive; they produce signals that are parametric measures of such physical phenomena as reflection, transmission, and the like.

The transducer thus produces a stream of data related to selected optical properties of the material to be inspected. The task of the automatic inspection system is to identify within that data stream the transduced signal values that specify the acceptability or unacceptability of the material subjected to inspection.

Where human vision is involved, the corresponding data stream is very

[2] *Business Week*, No. 2313, 12 Jan. 1974, p. 28N.
[3] *Modern Plastics*, Vol. 51, No. 8, Aug. 1974, p. 38.
[4] Nordqvist, K. G. and Millgard, L., *Iron and Steel Engineer*, Vol. 51, No. 6, June 1974, p. 67.
[5] *Business Week*, No. 2282, 2 June 1973, p. 80.

complex and not understood clearly at all, except that through "training" and "experience" humans can "learn" to identify blemishes of various kinds. Presumably, a great deal of subjective judgement is involved, whether conscious or not.

One pragmatically successful attempt to automate visual inspection is the laser scanning system shown in Fig. 1. In this sytem, the technique is to scan the material with a moving light beam derived from a laser "flying spot scanner" and to detect the reflected or transmitted beam which has been modified by the optical characteristics of the material being scanned. The laser beam is swung through an arc of 48 deg by means of rapidly rotating, faceted mirror, the only moving part in this system.

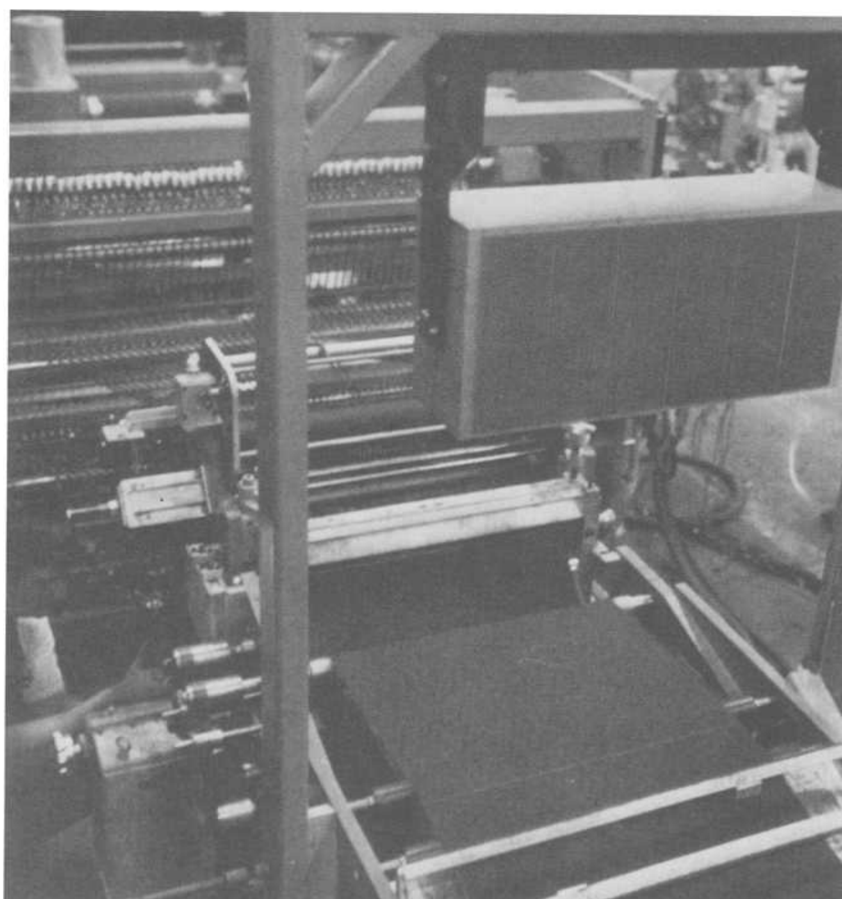


FIG. 1—*Laser scanner, showing laser beam inspecting bank transfer ribbon. Laser detector is beneath opaque web.*

The scanner can move at extremely high speeds—5000 or more scans per second—and provides accurate information on the location of the light spot at any instant. The arrangement permits 100 percent coverage of materials as wide as 160 in., moving at speeds of several hundred feet per minute (Fig. 2).

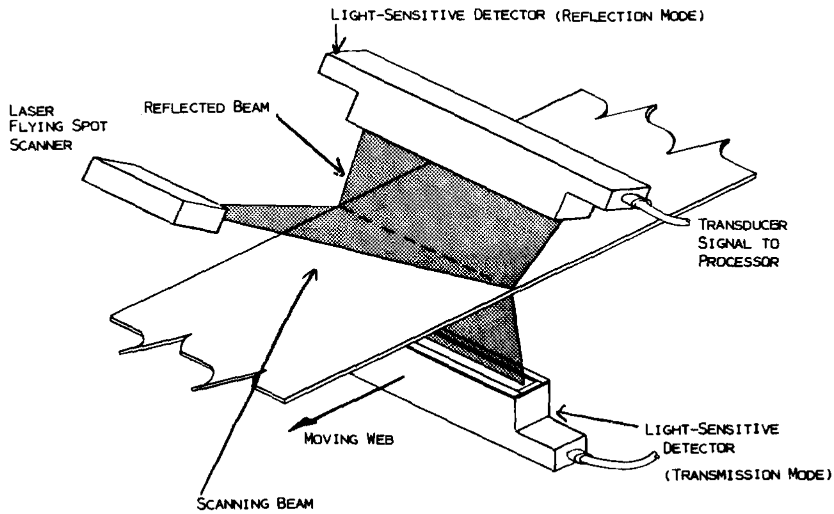


FIG. 2—*Flying spot scanner and detector as used in the automatic "visual" inspection system.*

The scanning beam may be transmitted through the moving material or reflected off its surface. In either case, the energy in the beam is collected and directed onto the transducer, a photomultiplier tube. The unique design of the receiver provides a narrow (1 in. wide) sensitive area that can be as wide as necessary to span the entire width of the moving web, up to 160 in. wide in some applications. The output of the photomultiplier is a small current that varies directly as the intensity of the light striking its photocathode.

In the case of an ideal, flawless material, the signal thus obtained is constant throughout each scan (Fig. 3) because the received light is of exactly the same intensity everywhere across the material. (A correction factor for the difference in path length, the so-called cosine effect, is included in the system.) However, in the case of any real material, the optical characteristics are not perfectly constant everywhere. For example, the surface is neither perfectly smooth nor of perfectly constant reflectivity. Therefore, the signal output contains a varying component that depends on the composite optical characteristics of the material being scanned (Fig. 4). Because the material tends to be very much the same along its length, the varying signal component tends to repeat with little change

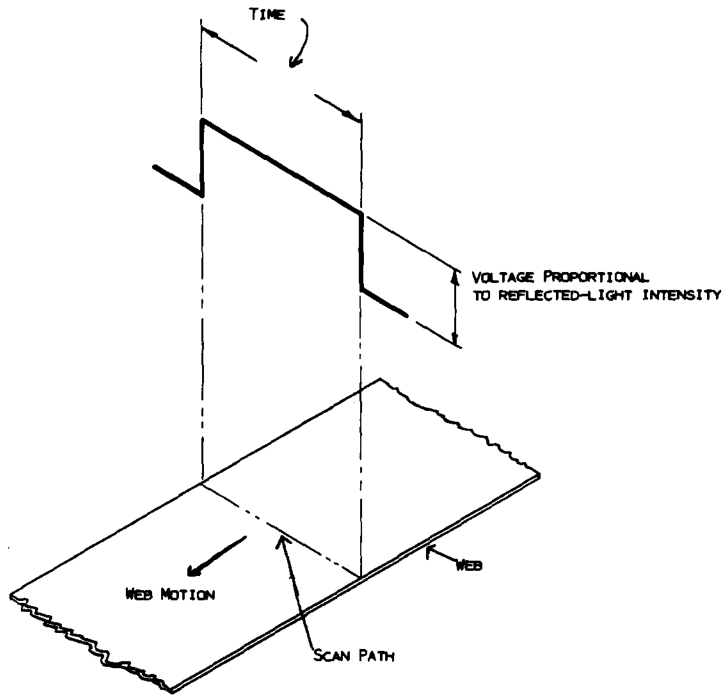


FIG. 3—*Idealized signal output from scanner/receiver.*

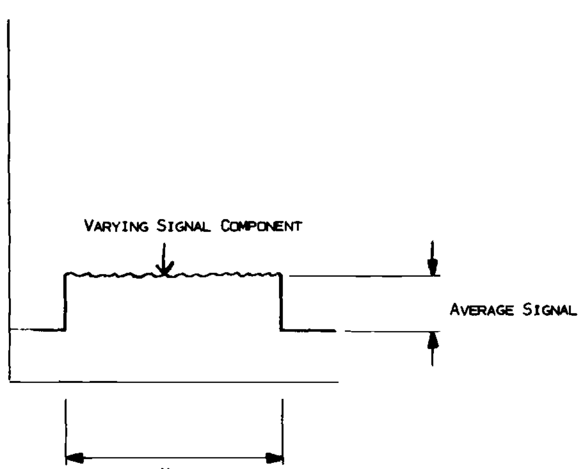


FIG. 4—*Typical signal obtained by scanning an actual material.*

from one scan to the next, and sequential scans of unblemished material display great uniformity of signal output from scan to scan.

Any anomaly in the signal voltage from one scan to the next is therefore indicative of some change in the optical characteristics of the material being scanned, as long as the material is known to lie flat and is neither buckled nor warped. (Fig. 5).

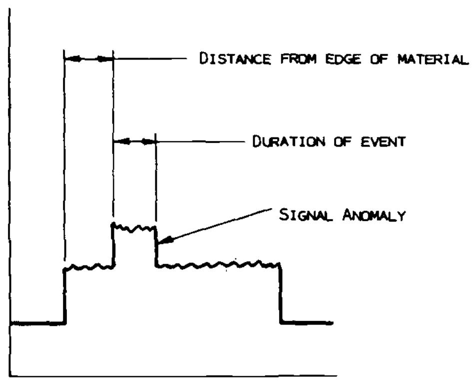


FIG. 5—*Signal anomaly.*

Thus, if a dirt spot on the material passes beneath the scanner, the signal output of the detector changes during the time that the dirt spot is present because the dirt spot absorbs more or less energy from the scanner beam than does the unblemished material. A surface anomaly, then, gives rise to a signal anomaly that we may define as an event. It is worth noting that in the context of visual inspection a surface anomaly, by definition, cannot have the same optical characteristics as the unblemished surface, for if it did, it would not be "visible."

Each blemish produces an anomaly in the signal output of the detector on each scan. A blemish having a length greater than the thickness of the scanning beam produces a signal anomaly in each successive scan until it has passed completely beneath the scanner and no longer affects the beam (Fig. 6). These signal anomalies, each of which is an event, constitute the data stream upon which the signal processing section of the automatic inspection system operates to identify those blemishes that require the material to be rejected (or the process to be adjusted).

From this scan-by-scan data stream, a great deal of information may be extracted by means of electronic data processing techniques, for example: from the "duration" of an event within a single scan, the width of the blemish may be defined; from the point within the scan at which the event commences, the distance of the blemish from the edge of the material

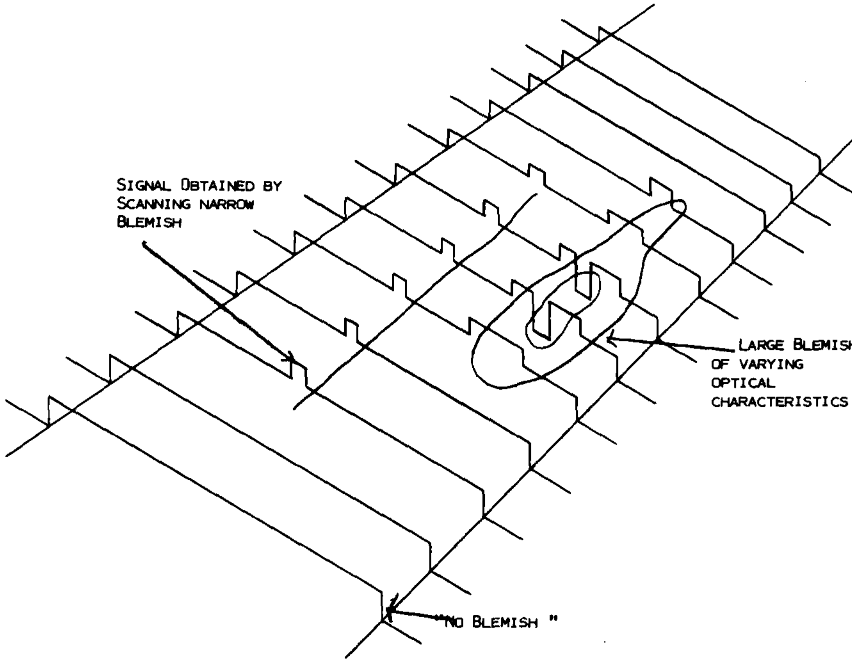
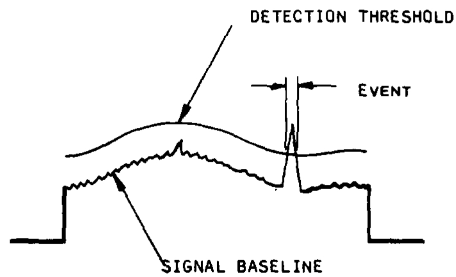


FIG. 6—*Effect of scanning a blemish.*

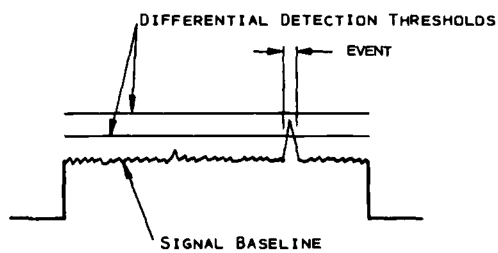
may be calculated; and from corresponding parameters in successive scans, the length and shape of the blemish may be deduced.

By setting detector thresholds at appropriate levels, the data stream may be made to exclude blemishes having less than a predetermined contrast with respect to the background of the material. Similarly, by defining thresholds and baselines in various ways, it is possible to enhance the probability of detecting various types and sizes of blemishes. Two examples of standard threshold adjustments are shown in Fig. 7. With the varying baseline effect shown in *A*, engineers have found it possible to adjust a system to detect blemishes in a wide range of surface structures. On the other hand, with the differential baseline arrangement shown in *B*, the system is able to detect faint differences in blemishes with a high degree of reliability.

A good example of the kind of sensitivity that human vision provides is the ability of most inspectors to detect long, faint streaks (a roller mark along one edge of the surface, for example). While such a mark produces only a very small signal in each scan of an automatic inspection system, the appearance of the corresponding signal in successive scans permits the use of simple signal averaging or autocorrelation techniques to reveal the existence of the blemish. Here, too, then, the auto-



A. DETECTION THRESHOLD FOLLOWS BASELINE VARIATIONS



B. DIFFERENTIAL THRESHOLDS LIMIT "EVENTS" TO THOSE THAT CROSS ONLY ONE OF TWO THRESHOLDS OF SPECIFIED LEVELS

FIG. 7—*Two threshold setting techniques used in systems.*

matic inspection system provides accuracy and reliability entirely equivalent to that of the human inspector.

In some applications, blemishes are of such form that their identification, even by a human inspector, requires them to be viewed from two independent perspectives. An example of such a blemish is one in which the height of the blemish above the surrounding surface conclusively distinguishes it from a surface discoloration. For such a blemish to be identified, the human inspector must move his head to obtain a different perspective, or, in an extreme case, it might be necessary to halt or slow the web in order to verify the suspicion.

The automatic inspection system permits two or more detectors to be used to view the same scan line, each detector with its own threshold characteristics (see Fig. 2). The outputs of the two detectors, exactly simultaneous, can be processed together to reveal whether the apparent blemish is real or a "false alarm."

Standardization

It has been shown that it is possible to build an automatic inspection system that will detect a wide variety of blemishes in materials moving beneath its scanner at very high speed. However, two requirements must also be met: first, to relate the detection of blemishes by such a system to the largely subjective "standards" for visual inspection by humans, and then to relate the system's performance to an objective measurement standard.

"Training" an Automatic Inspection System

To accomplish the first, it has been found feasible to resort to a process analogous to that in which humans are trained as visual inspectors. To train a human as an inspector, a sample of the material, containing a blemish of the anticipated type, is examined by the trainee, who then learns the visual characteristics of the blemish as it appears on the material. Sometimes the process involves a real sample that contains real defects; sometimes simulations, like photographs or drawings, are used; and sometimes verbal description will suffice.

In any case, an experienced inspector usually observes and acts as a "secondary standard" for the trainee. His role is to verify the trainee's success and to correct or "fine tune" the trainee's work until it attains a satisfactory match with that of the secondary standard. Unfortunately, such judgements of performance are at least as subjective as are the very inspection judgements themselves. Not all "experienced" inspectors are of equal skill and reliability, nor are their trainees.

The analogous technique is to establish the signal detection and processing parameters of the automatic scanning system by operating it on a sample of the material containing blemishes of the type that must be recognized. These blemishes, of course, will have been detected previously by a human inspector, who thus serves as the secondary standard for the automatic inspection system.

By adjusting the physical, optical, and electronic parameters as required to match the performance of the system against the secondary standard, the system is "trained" as an inspector. When the system subsequently is placed on line, it is put through a similar procedure in which it is "fine tuned" for accuracy and reliability against the secondary standard.

This approach, in fact, has worked admirably well in a range of system applications in paper, plastics, and metals processing, and a number of installation reports have been prepared to document the success of the technique. Experience seems to indicate that it is possible to fine tune an automatic inspection system to a higher standard of performance than initially anticipated by the human inspectors who serve as secondary standards. For example, in one application, the quality control department assumed that blemishes of a particular type would be distributed evenly throughout a given lot of material subjected to a single process.

The assumption was discovered to be erroneous, a fact not previously ascertainable because 100 percent visual inspection had not been feasible until an automatic system was installed. As shown in Fig. 8, the blemish specification of 10 blemishes/yd was exceeded far more often in some coils of material than in others, the range of variation being more than 10:1, even though the ten coils of the lot were processed one after another. The material inspected was moving at more than 400 ft/min, and each coil was some 7000 ft long.

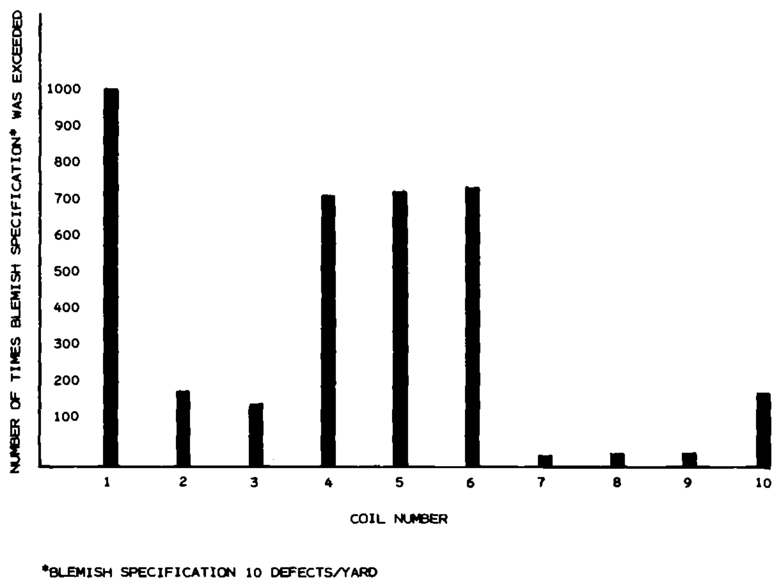


FIG. 8—*Nonuniformity of a typical industrial process as uncovered by 100 percent automatic visual inspection at 400-ft/min line speed.*

Calibrating an Automatic Inspection System

Clearly, in this case, the "trainee" soon surpassed its mentors' skills. However, unless some objective measures of system characteristics are available, it is difficult to say whether or not a similar level of performance always can be expected in other applications. Therefore, my organization routinely defines certain system parameters by precise measurement techniques. Of particular interest in this regard are the following:

1. Scanning beam characteristics
   a. Beam cross section limiting dimensions at the point at which it touches the material to be scanned
   b. Beam intensity

c. Scan geometry
2. Detector sensitivity and frequency response

A well known secondary standard for measurements of optical performance is the "resolution grid" commonly used to test optical systems such as cameras and microscopes. A typical resolution grid consists of a pattern of lines or bars of precisely known dimensions, spacing, and orientation. The "resolution" of the optical system is defined then by the fidelity with which it can image the test pattern.

While laser scanning systems for inspection produce no visible images, an analogous procedure still may be followed for a major portion of the system calibration. In this case, the "resolution grid" consists of a photographic plate in which bars of precisely known dimensions and orientation have been reproduced as shown in Fig. 9. The plate may be adapted

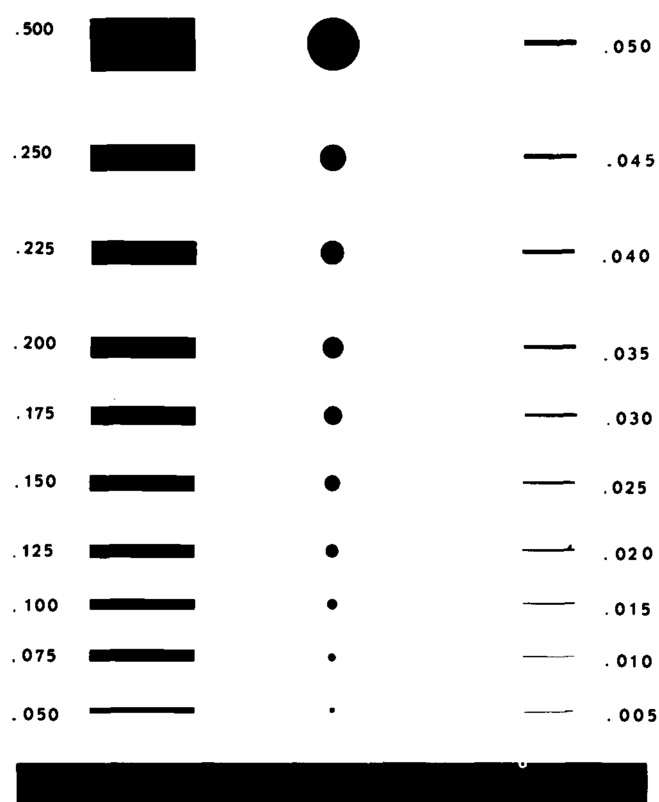
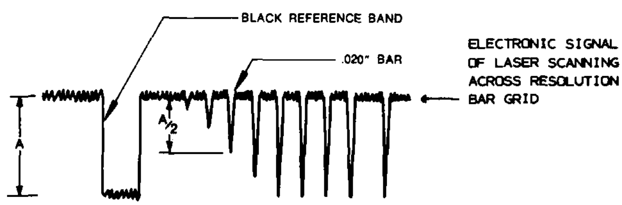


FIG. 9—*Resolution grid.*

either to reflection systems or to transmission systems and may provide either "positive" or "negative" bars.

Swept orthogonally across such an array of bars, the scanning beam produces an output signal from the detector as it is reflected or transmitted by each bar. The signal output from the detector is then a function of the relationship of the beam and bar dimensions and the intensity distribution within the beam as shown in Fig. 10.



TO DETERMINE THE SPOT SIZE OF THE BEAM, IT IS NECESSARY TO INTRODUCE A RESOLUTION BAR GRID AS IN FIGURE #9. WITH THE SCANNER AND RECEIVER FIXED AT THEIR ESTABLISHED INSPECTION ANGLES, A CLEAR PLASTIC TEST TARGET ON A WHITE SHEET OF PAPER IS INTRODUCED INTO THE SCANNING BEAM.

TO DETERMINE THE WIDTH OF THE SPOT, THE BARS ARE INITIALLY POSITIONED IN THE SCAN. IN BOTH INSTANCES, DOTS AND BARS SIGNIFICANTLY LARGER THAN THE LASER BEAM SIZE WILL PRODUCE SIGNALS OF EQUAL AMPLITUDE. AS THE DOTS AND BARS BEGIN TO BECOME EQUAL TO OR SMALLER THAN THE LASER BEAM SIZE, THE OBSERVED SIGNAL AMPLITUDE BEGINS TO DECREASE. A DOT OR A BAR PRODUCING A SIGNAL AMPLITUDE HALF OF WHAT IS CAUSED BY THE BLACK REFERENCE BAND IS CONSIDERED TO BE THE TRUE SPOT SIZE. TO ILLUSTRATE THIS, FIGURE #10 SHOWS THE SPOT WIDTH TO BE 0.020".

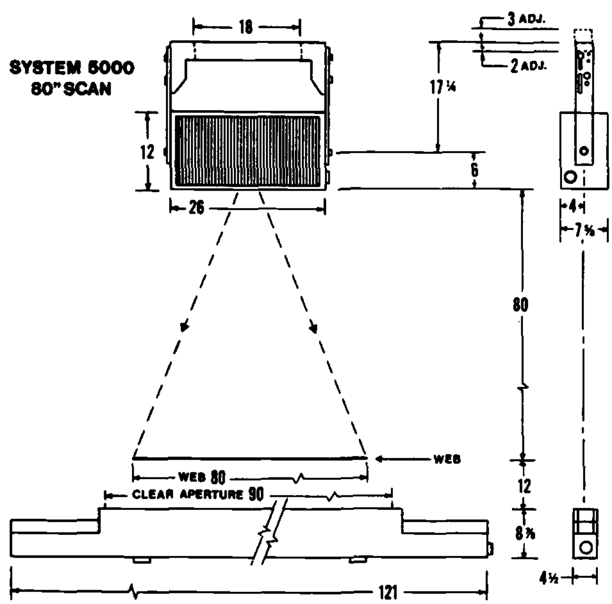
FIG. 10—*Relation between resolution bar dimensions and beam dimensions.*

An equivalent record may be created by scanning the beam slowly across the selected bars and recording the signal output of the detector on an oscillograph. Examination of the records then reveals the across-web dimension of the beam cross section, since maximum response is obtained when the bar dimension is equal to or greater than that of the beam. A similar plate is used to determine the beam dimension in the down web direction.

As an example, in one system the scanner head contains mechanically adjustable lenses which permit independent adjustment of the laser beam's geometry in both a down-web and cross-web dimension. Use of the resolution grid therefore permits the beam dimensions to be preset to a high degree of precision.

Once the dimensions of the beams cross section have been established, the relative beam intensity is determined. Only the relative power level of the beam need be known in most cases, since the nominal output level of the helium-neon (He-Ne) laser is established during its manufacture and test. Further, as a practical matter, the signal detection and processing functions are linear over a very wide range of beam intensities. In cases in which the absolute power of the beam must be known, a "standard" detector may be used to provide absolute accuracy on the order of ± 1 dB.

Scan geometry is a composite function of scanner axis location and orientation with respect to the material to be scanned. The scanner is mounted on carefully designed and manufactured brackets and contains provision for adjustment (Fig. 11).



NOTE: ALL DIMENSIONS ARE IN INCHES

FIG. 11—*Typical installation drawing.*

When the scanner has been mounted in place, the exact orientation of the scanning beam may be observed visually as may be seen from Fig. 12. Any necessary final adjustments of scanner or receiver now may be made by observing the orientation of the scanning beam and monitoring the electrical output of the detector.

The detector portion of the system is calibrated fully in the laboratory as part of its manufacture and test procedure. Using an appropriate He-Ne light source, the detector is illuminated and its sensitivity and fre-

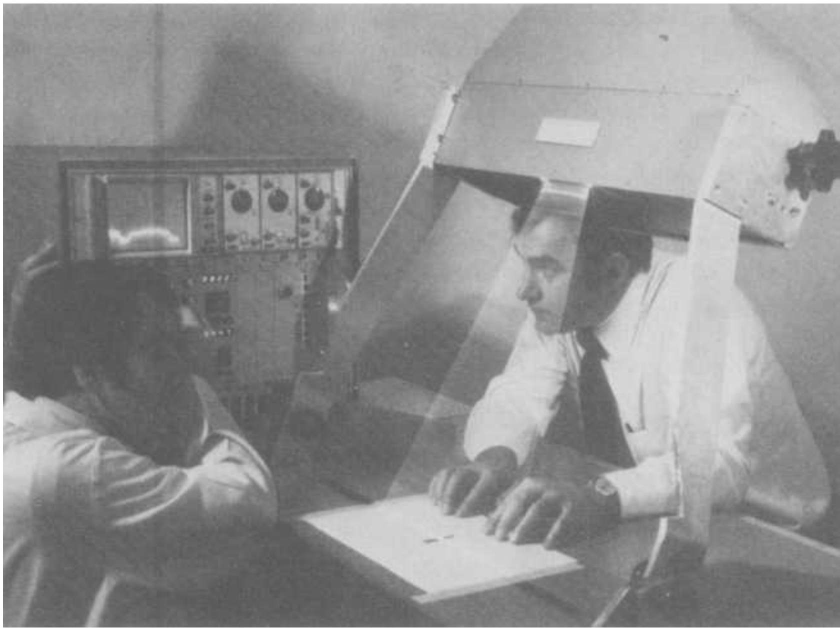


FIG. 12—*Alignment adjustments being made by visually observing the laser beam while inspecting samples in an applications laboratory.*

quency response characteristics are plotted as for any other conventional electro-optical transducer and amplifier.

The great sensitivity of the transducer/amplifier portion of the system requires that it be protected against the effects of electrical interference, and the circuitry contains such provisions. Each system must be able to pass a stringent test for susceptibility to electrical interference; these tests are made by means of standard "radio frequency interference" test equipment and procedures.

Transfer Standards for Automatic Inspection Systems

The ability both to "train" and to calibrate the automatic inspection system raises the question of whether or not a "fine-tuned" and calibrated "trainee" can replace its mentor as a superior secondary standard for other automatic inspection systems. In order to do so, it is necessary to develop some kind of objective standards by which the fine tuning may be transferred between systems.

During the initial process of system training, it is possible to deduce a great deal of objective information about the visual inspection parameters of the detected blemishes. Size, shape, contrast ratio, reflection/absorption/transmission characteristics, specularity, surface roughness, and so forth may be measured separately against traceable standards; then these measurements may be correlated against the various signals developed by the automatic inspection system. From analysis of such correlations, it is possible to make reasonable judgements concerning the objective nature of the detected blemishes and the signals they produce.

If the physical characteristics of the inspected material are known, and if detected blemishes and corresponding electrical signals have been correlated against the subjective judgements of human inspectors, it should be possible then to simulate the pertinent blemish characteristics so that the inspection system will produce the appropriate electrical signals when scanning the simulations. These simulated blemishes now can serve as quasiobjective standards for this system and as transfer standards for other systems of similar design and operation.

A crude example may be hypothesized as follows.

1. Suppose the characteristic blemish that results in rejection is a mark or bruise that roughens an otherwise smooth surface.

2. Suppose that human inspectors are able to recognize such a blemish when it is only 0.050 in. wide and that the automatic system has been adjusted to detect every such blemish.

3. If measurement of such blemishes reveals that, in order to be detected they must scatter light from an 0.040-in.-diameter scanning beam so that the reflected brightness of the blemish is 40 percent less than that of the surrounding material, it should be possible then to create an empirical simulation, perhaps as a neutral-density wedge, for example, that produces a corresponding rejection signal by the system.

4. This simulation, presented to the system, now permits adjustment of the system to permit detection of such a blemish on the actual material. In principle, it also should permit the adjustment of a similar system to a corresponding level of performance. The simulation is, therefore, a kind of transfer standard for visual inspection by an automatic inspection system.

As a transfer standard, such a simulation can be stored, as the actual material itself might not permit, if, for example, the material being inspected is subject to surface deterioration with aging. It also can be duplicated with great precision, which might also be impossible in the case of an actual sample. Further, objective measurements of its physical characteristics offer the prospect of traceability in certain ways, although not in ways not entirely consistent with the traceability of more rigorous standards.

By equivalent methods, corresponding secondary or transfer standards might be prepared to permit detection of various types of blemishes on diverse materials. Each such standard would then permit the training of an automatic inspection system for the detection of a particular class of blemish on a particular material. While such a process, by its nature, is limited in application, it does permit the objectification of a whole class of judgements that were once wholly outside the realm of standardization.

Stanley Ruthberg[1]

Hermetic Test Procedures and Standards for Semiconductor Electronics

REFERENCE: Ruthberg, Stanley, "**Hermetic Test Procedures and Standards for Semiconductor Electronics,**" *Nondestructive Testing Standards—A Review, ASTM STP 624*, Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 246–259.

ABSTRACT: The hermetic testing of semiconductor devices is a challenging subject area because of the need for leak testing large numbers of sealed packages to very fine leak rates, where the packages are of a wide range of materials and internal volumes. The types of measurement methods to be discussed are those presently in use and are represented in both military and voluntary standards. Four of these methods will be assessed briefly along with the relevant standards as to advantages, disadvantages, range, precision, and agreement. The four methods are bubble, weight gain, helium leak detector, and radioisotope test procedures. Present interlaboratory test efforts that have been undertaken to provide suitable test data for guidance in the drafting of new American Society for Testing and Materials (ASTM) standards will be summarized. Future directions will be indicated.

KEY WORDS: nondestructive tests, standards, hermetic seals, semiconductor devices, leakage

Hermetically sealed enclosures are particularly important in semiconductor device technology because of the degradation that occurs in the devices due to the presence of small concentrations of water. Many of today's devices are encapsulated in plastic as a less expensive means of protection when it is adequate for the intended use, but high reliability devices are incorporated typically into hermetic enclosures. Among the package materials used are glass, ceramic, and metal. Seals are made by soldering, welding, or fusing. Structures are varied, and internal volumes available for gas collection generally range from less than 10^{-3} cm^3 to several cubic centimetres. A typical assortment of such packages is shown in Fig. 1.

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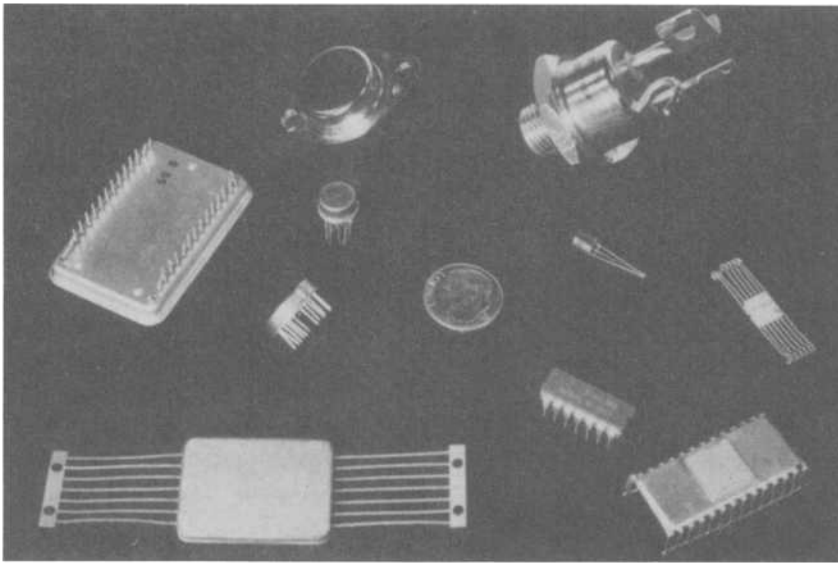

FIG. 1—*Assortment of some typical semiconductor package types.*

There are smaller packages than these, and there are larger. As can be seen, the number of leads that pass through a hermetic seal can be many.

The test of the seal effectiveness of semiconductor packages is accomplished by a number of methods. Presumably, when specified for high reliability use, all devices with indicated leak rates greater than some prescribed value are rejected, where this limit may be as small as 1×10^{-9} Pa · m^3/s.[2] Such screening has been necessary for the achievement of high reliability systems, for example, the fallout from military standard hermetic tests of integrated circuits is about 5 percent of the circuits tested on the average, and the cost for such testing is significant, being typically $0.20 per circuit. It is interesting to note, though, that package failure still leads to some 13 percent of the operational failures that do occur in high reliability integrated circuit electronic systems [*1*].[3]

Although hermetic test activity is both necessary and extensive in the semiconductor industry, there is still a lack of a sound technical basis for clear-cut specifications on maximum allowable leak rates. The reason for this is that no data are presently available which can be used to relate

[2]Units of flow rate are conventionally atm · cm^3/s or torr · l/s, but in the International System (SI) of metric units the unit of flow rate is the Pa · m^3/s. 1 Pa · m^3/s = 9.86926 atm · cm^3/s and 7.50064 torr · l/s. Such units for pressure as pounds/square inch absolute (psia) and pounds/square inch gage (psig) also are used in the text as taken from reference.

[3]The italic numbers in brackets refer to the list of references appended to this paper.

moisture infusion to leak rate or leak rate to component life, except in the broad category that package leak rates greater than 1×10^{-7} Pa · m³/s are harmful.

Relevant Standards

There are at least 11 standards documents in general use for direct application to the leak testing of semiconductor packages. Of these, two are military and one is a National Aeronautics and Space Administration (NASA) standard, each of which includes many test methods for various properties of semiconductor electronics in addition to those of hermeticity. These three documents are mandatory for their device suppliers and for use within the respective organizations. The remainder are voluntary standards originating in the American Society for Testing and Materials (ASTM) Committees E-7 on Nondestructive Testing and F-1 on Electronics. There are in addition some 8 more ASTM and American Vacuum Society (AVS) standards for selection of test methods for calibration of test equipment, for test specifications, and for definitions. All of these standards are listed in Appendix I, and from an examination of these it is apparent that a duplication of effort exists. The voluntary standards leave the setting of test limits to the user based upon need, but due to the lack of a technical basis for test limits, the military standards set these limits arbitrarily. Because of their specificity and their impact on procurement for high reliability systems, the military standards are now of broadest use in the semiconductor community.

Assessment

The cited standards include bubble, dye, weight gain, halogen leak detector, helium leak detector, and radioisotope test procedures. Because of the small volumes and package constructions, most of the test methods require back pressurization, which is a process of driving a tracer gas or fluid into the interior by pressurization, and detection of the tracer on re-emission. The bubble, dye, and weight gain methods are appropriate for the gross leak range, which is taken to be $\geq 10^{-6}$ Pa · m³/s. The leak detector and radioisotope methods are essentially for the fine leak range ($\leqslant 10^{-6}$ Pa · m³/s), but can be used for detection into the gross leak range depending on the size of the package internal volume.

Dye penetration techniques are more appropriate to the destructive testing of individual components for diagnostic purposes, where decapping or other physical alteration of the package occurs. Dye techniques are used, however, for devices with transparent walls. The halogen leak detector is not popular for semiconductor components. Of the remaining tests on the list just mentioned, the bubble, helium leak detector, and radioisotope procedures are the most widely used, and the weight gain method is now receiving increasing attention. These latter four test methods and related standards now are assessed briefly as a means for introducing the problems and weaknesses in present standards efforts. The range, advantages, disadvantages, and test capabilities are listed in Table 1. The data on measurement capabilities are approximate values as condensed from a recent experimental evaluation of the procedures of the Military Standard on Test Methods and Procedures for Microelectronics (MIL-STD-883A) [*2*].

The first observation is that none of these methods typically is capable of detecting large leaks ($> 10^{-2}$ Pa · m^3/s), so that other procedures must be used. In manufacturing practice, reliance is placed upon visual microscopic inspection for flaws that would permit such large leaks, for example, a leak rate of 10^{-2} Pa · m^3/s corresponds to a capillary dimension of 0.003 cm diameter for a channel length of 0.05 cm. No guidelines are available for visual inspection in the voluntary standards, nor are the external visual check methods of the mandatory standards particularly oriented to hermetic test.

Bubble Emission Tests

There are two classes of bubble tests. One is simply direct immersion of the test object into a hot, clear, inert fluorocarbon liquid of low surface tension. If a leak is present, bubbles will appear as the gas in the device expands on heating. The leak test range is narrow. The second class is superior in test range and detection of leakers and, as the preferred test method, it is included in Table 1. For this, the component is exposed first to vacuum and then back pressurized with a high vapor pressure fluorocarbon liquid so that if a leak is present the fluorocarbon is driven into the component. On immersion in a hot, low surface tension indicator fluid, the fluorocarbon bubbles out of a leaky device.

Although bubble size and frequency have been related to leak rate under ideal conditions [*3*], such bubble tests are subjective in practice. They are tedious, results are very dependent upon the geometry of the package, and a gross leak comprised of several fine leaks can be missed. The use of liquids requires that this test be performed after fine leak tests have been completed to avoid the plugging of leaks; it also provides the possibility of residual contamination in the accepted components having undetected leaks.

Weight Gain Test

The weight gain test requires careful cleaning of the package before weighing to a tenth of a milligram. After evacuation and pressurization with a suitable low vapor pressure fluorocarbon fluid, the package is

TABLE 1—*Assessment of hermetic test procedures for semiconductor devices by two liquid bubble, weight gain, helium leak detector, and radioisotope methods.*

Test Procedure	Range	Advantages	Disadvantages	Overkill[b]	Capability[a] Escape[c]	Repeatability[d]
Pressure bubble (two liquid)	10^{-5} to 10^{-2} Pa · m^3/s	simple inexpensive fast	subjective qualitative tedious need smooth exterior difficult observation elevated temperature residual contamination plugs fine leaks	$\leqslant$ 26%	$\leqslant$ 20%	65 to 96%
Weight gain	5×10^{-7} to 10^{-2}	direct wide range quantitive published curves	slow needs serialization sensitive balance residual contamination plugs fine leaks.	$\leqslant$ 12%	0	...
Helium leak detector	10^{-9} to 10^{-3}	inert gas quantitive wide range flexible ~1000 pieces/h	long pressurization times indirect gas sorption effects high maintenance	...	up to 50%[e]	26 to 94%
Radioisotope	10^{-10} to 10^{-3}	direct inert gas quantitive simple detection large test batches discriminates surface gas ~10000 pieces/h	radioactive hazard gas models inappropriate narrow range, per cycle gas sorption effects high maintenance	...	up to 50%[d]	60 to 98%

[a] Measurement capabilities are approximate as condensed from Ref 2. Actual values depend greatly upon the nature of the test package and particular test procedure, and further analysis of these data requires careful reading of the original evaluation in Ref 2.

[b] Overkill, indication of hermetically tight packages as leakers.

[c] Escape, failure to detect a leaker.

[d] Repeatability, based upon repeated measurements falling within same decade for helium leak detector and radioisotope methods and on repeated detection for bubble method.

[e] Escape rate depends upon selection of pressurization parameters and on package type. See text and Ref 2 for detail.

dried again and weighed to a tenth of a milligram to detect the weight of the fluorocarbon driven in through a leak. Thus, a sensitive balance of relatively large mass range is required. If reweighing is accomplished within a time of the order of a few minutes after pressurization, the test range is quite broad. The weight gain could be related to leak rate through viscous flow calculation provided the leak geometry were simple, but since this is seldom the case, an experimental procedure is used to determine the fluid flow rate through capillary leaks with results such as shown in Fig. 2 [*4*].

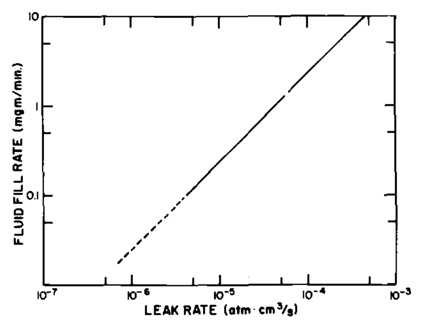

FIG. 2—*Weight gain hermetic test method. Fluid fill rate with fluorcarbon through glass capillary leaks under 100-psig pressurization.*

These particular data were obtained with glass capillaries for which leak rates were measured with the helium leak detector. The weight gain is the only available method that is quantitative across the gross leak range; however, it suffers in the need for serialization of the parts for pre- and post-weighing and is a relatively slow test method. No effort has been given to the documentation of this method as a voluntary standard, as yet.

Helium Mass Spectrometer Leak Detector Test

The use of the helium leak detector is well documented. This instrument has the widest leak rate application range for general use although in Table 1 use has been restricted to the back pressurization method [*5*] as used for electron devices. For this procedure, the objects to be tested are prepared in a simple pressure bomb with helium gas, removed, tranferred to the helium leak detector, evacuated, and tested for effusing helium. A numerical indication is obtained from the leak detector which can be related to true leak rate only if an appropriate theoretical relationship is available to relate these two quantities. The correlation depends upon the regime of the gas flow into the test object, the pressurization parameters, internal free volume, the delay time between pressurization and readout, and the flow mechanism for helium effusion from the test part. Since enough of the helium first must be driven into the part to give discernible effusion, the pressurization times can be quite long for components of large internal volume when tested to package leak rates $\lesssim 1 \times 10^{-8}$ Pa $\cdot$ m^3/s. In all of the cited standards for helium leak detector use, the package leak rate is determined from an expression based upon the molecular flow regime. It is interesting to note from this theoretical relationship, not for purposes of detail but for the purpose of observing the general form of solution, how resultant data might relate to other methods, and how the standards are effected. The equation is

$$R = P_b \cdot L \left[\frac{1}{P_0} \left\{ 1 - \exp\left(- \frac{L}{P_0 V} T \right) \right\} \exp\left(- \frac{L}{P_0 V} t \right) \right]$$

where

R = machine reading for helium,
L = package leak rate under conditions of one atmosphere of helium pressure upstream and zero pressure downstream,
P_0 = one atmosphere pressure,
P_b = bombing pressure,
V = internal free volume,
T = pressurization time, and
t = delay or dwell time between pressurization and readout.

The first exponential term describes the pressure rise of helium within the package due to pressurization, while the second exponential term describes the fall off of pressure due to effusion. Since this expression is based upon the molecular flow regime, it is in principle only applicable to fine leaks; whereas, in practice it is applied to the whole leak range. Solutions are represented in Fig. 3 for a range of values of the appropriate quantities sufficient for most electron device packages. Here E, the internal fractional helium partial pressure per atmosphere of pressurization, is the value of the bracketed part of the equation including the exponential terms. A double valuedness in leak rate, L, as a function of machine reading, R, and package volume, V, is indicated which predicts that a gross leaker may not be distinguishable from a fine leaker without further manipulation of test variables. In practice it is assumed that a minimum and maximum detectable leak rate exists and the range of leak rates between these two limits will be detected for any given bombing pressure P_b (in atm), internal free volume, V, and minimum detectable machine reading, R_{min}.[4] Prediction of minimum and maximum detectable leak rates has been made somewhat simpler in ASTM Recommended Practices for Determining Hermeticity of Electron Devices with a Helium Mass

[4]See Appendix II for an example of use of Fig. 3.

Spectrometer Leak Detector (F 134-72T) by approximation to the molecular flow equation. In reality one would expect these characteristics to be

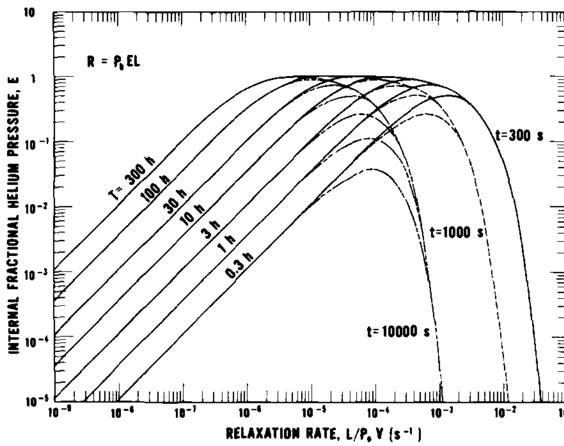

FIG. 3—*Helium leak detector hermetic test method. Internal fractional helium pressure versus relaxation rate as a function of pressurization time,* T, *and dwell time,* t, *as determined from molecular flow gas exchange (see Appendix II).*

of somewhat different shape and of somewhat different predicted values because of the shift in gas flow regime with leak rate.

Satisfactory test results require proper and frequent maintenance and calibration of the leak detector. Two recommended standard procedures for calibration are available (Appendix I, Items 12 and 14) but neither by itself leads to a complete calibration of the leak detector for hermetic test. Although calibration requires reference leak standards, no recommended procedure is available for deriving reference leak standards for the range $< 1 \times 10^{-7}$ Pa · m³/s.

Radioisotope Test

Although the radioisotope method of leak testing has been in use for some 20 years, the number of test installations was limited until recently. The test sequence is essentially the same as for the helium leak detector; however, the radioactivity of the tracer gas, Kr^{85}, leads to the inverse situation in instrument sophistication from that of the helium leak detector. For this method, it is the pressurization equipment that is complicated because of the need to capture and recycle the Kr^{85}, but detection is done simply with a radiation counter in room environment. The radioisotope method for leak testing hermetic packages is a basically more direct method than the helium leak detector in the sense that the gas is measured while inside the package. Thus, smaller concentrations suffice, so that the minimum detectable leak rate is lower than that of the helium leak detector for the same pressurization parameters. Package volume is not a factor. Since detection is at atmospheric pressure, sample handling rates are much greater, but at the same time background noise and counter range for safe operation cause the leak test range to be limited to about two decades per test condition. This requires a multiple test sequence to cover the test range desired.

Again, the count rate and package leak rate can be related only through appropriate gas flow equations. The recipe that has been traditional for this test method is based upon the viscous flow regime [6] and is as follows

$$R = KST \frac{L}{P_0^2}\left(P_b^2 - P_i^2\right)$$

where

K = counting efficiency in counts/μC_i/min associated with a given package type,
S = specific activity in μC_i/atm · cm^3 of the Kr^{85}-air mixture used for pressurization, and
P_i = initial interior pressure.

There are a number of deficiencies; the flow model assumed is more appropriate for the gross leak range, no account is taken for gas escape and dwell time after pressurization, normal exponential pressure dependence is approximated on the assumption that the interior pressure change is small, and no provision is incorporated for the differential flow rate of Kr^{85} and air in fine leaks where molecular flow should prevail. Precautions should be taken when using the method for testing larger volume packages because of the possibility of overfill, which would make the packages too radioactive. Possible fill rates are given in Fig. 4 as the amount of gas that can pass through a given capillary leak, L, in a time, t, when the downstream pressure is held at one atmosphere and the upstream pressure is P_b. The gas flow has been calculated on the basis of combined molecular and viscous flow. Specific activities of charging mixtures may range from 100 to 1000 μC_i/atm · cm^3. Thus, a test sequence is required where the first step is with a short pressurization time and low pressure to detect gross leaks; the second step is with longer pressurization time and higher pressure for intermediate leak rates, etc.

Weaknesses in Existing Standards

There are several areas where continued improvement is needed in hermetic test standards.

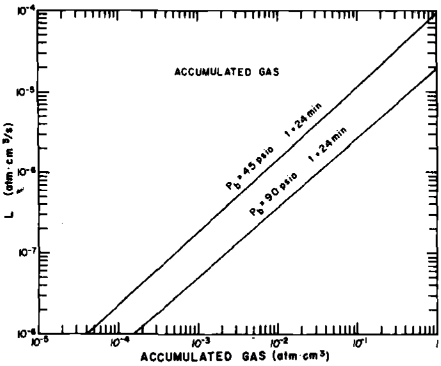

FIG. 4—*Radioisotope hermetic test method. Amount of gas passing through a given capillary leak,* L, *for downstream pressure of one atmosphere and upstream pressure of* P_b *in a time,* t, *as determined by transition flow. Specific activities of charging mixtures may range from 100 to 1000* $\mu C_i/atm \cdot cm^3$.

A major problem in the helium and radioisotope methods is caused by the different assumptions on gas flow regimes which grossly complicate intercomparison efforts, lead to significantly large discrepancies in the actual leak test criteria, and cause large variations in product yield. A second problem existing in some standards is that insufficient directions are given for estimating the precision of the test as based upon observable uncertainties. This omission bears upon the lack of measurement correlation that has been obtained with the same test method when applied at different stations. A third weakness that occurs is that insufficient or no interlaboratory comparisons were made initially to evaluate some draft standards. Fourth, few of the standards are complete in themselves, which leads to confusion. Fifth, few of the documents are so specific in instruction that a laboratory test can be implemented from the document alone. And finally, a lack in the measurements system itself is that operational specifications on leak rate are not available so that arbitrary test specifications are set and proliferated, which further obscures test agreement.

Future Directions

A need has been expressed by the semiconductor community for a standardization of test procedures and for securing leak rate standards which, with possible correlation factors, could be used to standardize leak rate rejection levels in the industry [7]. This is a desirable goal, but it should be established on good metrological procedure rather than on arbitrary decision. It is better that test levels should be based upon real operational specifications as derived from experimental determination of moisture infusion as a function of leak rate [*8*]; leak rates then should be derived with measurement methods of demonstrated precision as based upon appropriate and commonly shared gas flow models; and, finally, intercomparisons of measurement methods must be obtained and correlations determined with test objects incorporating known leak rates.

Interlaboratory intercomparisons are being conducted now to test the helium leak detector and radioisotope methods. The purpose of the helium leak detector test is to evaluate ASTM Recommended Practice F 134-72T for package volumes equivalent to those of large hybrid devices, but it has been stalled by excessive helium sorption effects on the large volume specimens because of the materials used. It is expected that this effort will be reinitiated with more appropriate test objects.

For the radioisotope test method, an initial interlaboratory test has been completed involving 10 laboratories and 100 commercial packages. The purpose was to supply information for the drafting of a new test standard. A specific test sequence was developed, tried, and modified. The evolved version was employed in a strict, refereed interlaboratory test. Prior informal attempts at intercomparison generally resulted in agreements to within one to two orders of magnitude between any two stations, and repeatability was order of magnitude at any one station, as is indicated in Table 1 for the MIL-STD-883A evaluation. However, results from this interlaboratory test demonstrated overall precision and agreement of better than fractions of a decade [9]. Further testing is being initiated to evaluate the effects of package size and materials on test results. Emphasis in the first standard under development for the radioisotope test method is on precision. Later, it is hoped that a common flow model will be incorporated into both the helium and radioisotope procedures and that tests will be made on known leak rate packages.

Beyond these tasks, efforts should be initiated on several other developments. The weight gain method should be considered for a standarization effort; recommended methods for establishing the values of standard leaks for the range $< 10^{-7}$ Pa · m^3/s need attention; and, finally, test methods have evolved sufficiently for the measurement of moisture within packages to be considered explicitly [10–11] and this should be done.

APPENDIX I

Mandatory and Voluntary Hermetic Test and Related Standards

Mandatory Standards

1. Military Standard on Test Methods and Procedures for Microelectronics, Method 1014.1, MIL-STD 883A, 15 Nov. 1974.
2. Military Standard on Test Methods for Semiconductor Devices, Method 1071, MIL-STD 750B, 27 Feb. 1970.
3. NASA Standard on Sealing, Line Certification Requirements for Microcircuits, Reliability and Quality Assurance Publication, NHB 5300.4/3C, May 1971.

Voluntary Standards

4. ASTM Recommended Practice for Liquid Penetrant Inspection Method (E 165-75).
5. ASTM Recommended Practice for Testing for Leaks Using the Halogen Leak Detector (Alkali-ion Diode) (E 427-71).
6. ASTM Tests for Leaks Using the Mass Spectrometer Leak Detector in the Inside-Out Testing Mode (E 493-73).
7. ASTM Testing for Leaks Using the Mass Spectrometer Leak Detector or Residual Gas Analyzer in the Tracer Probe Mode (E 498-73).
8. ASTM Testing for Leaks Using Bubble Emission Techniques (E 515-74).
9. ASTM Test for Hermeticity of Electron Devices by Dye Penetration (F 97-72).
10. ASTM Test for Hermeticity of Electron Devices by a Bubble Test (F 98-72).
11. ASTM Recommended Practices for Determining Hermeticity of Electron Devices with a Helium Mass Spectrometer Leak Detector (F 134-72T).

Related Standards

12. AVS Helium Mass Spectrometer Leak-Detector Calibration (2.1-1963).
13. AVS Method for Vacuum Leak Calibration (2.2-1968).
14. ASTM Calibration of Helium Leak Detectors by Use of Secondary Standards (F 78-71).
15. ASTM Definitions of Terms Relating to Liquid Penetrant Inspection (E 270-74).
16. ASTM Definitions of Terms Relating to Leak Testing (E 425-71).
17. ASTM Recommended Guide for a Selection of a Leak Testing Method (E 432-71).
18. ASTM Reference Photographs for Liquid Penetrant Inspection (E 433-71 (1976)).
19. ASTM Recommended Guide for Preparation of a Leak Testing Specification (E 479-73).

APPENDIX II

Correlation of Package Leak Rate to Machine Indication for Helium Leak Detector and Back Pressurization

After the specimens are pressurized in helium for a time, T, removed from the pressure vessel, transferred to the helium leak detector, evacuated, and tested for effusing helium, the leak detector indication is, as based upon molecular flow

$$R = P_b \cdot L \left[\frac{1}{P_0} \left\{ 1 - \exp\left(-\frac{L}{P_0 V} T\right) \right\} \exp\left(-\frac{L}{P_0 V} t\right) \right]$$

where

R = machine reading for helium,
P_b = bombing pressure,
L = package leak rate under conditions of one atmosphere pressure upstream and zero pressure downstream,
P_0 = is one atmosphere pressure,
V = interior free volume, and
t = delay or dwell time between pressurization and readout.

Solutions are represented in Fig. 3 for a range of values sufficient for most electron device packages. Here E is the internal fractional helium partial pressure per atmosphere of pressurization as equivalent to the bracketed part of the equation so that

$$R = P_b \cdot L \cdot E$$

These characteristics may be used to predict minimum pressurization conditions necessary to detect a given package leak rate, to predict a maximum dwell time for a given gross leak, or to predict the band of detectable leak rates for any set of conditions.

The correlation of machine reading, R, to relaxation rate $L/P_0 \cdot V$ is reasonably direct for relaxation rates $< \sim 10^{-5}$ s^{-1}, where typically leaks are in the fine range and dwell times of several hours or more have little effect on the internal helium pressure. Beyond $\sim 10^{-4}$ s^{-1}, leaks are typically in the gross range and the internal helium pressure falls off rapidly so that dwell times are critical but dependence on pressurization time is not strong.

As an example of use of Fig. 3, one can ask for the pressurization time required at 5 atm absolute to detect package leak rates of $\sim 2.7 \times 10^{-8}$ atm · cm^3/s of helium (1×10^{-8} atm · cm^3/s equivalent air leak rate) or greater with a package type of 0.01-cm^3 interior free volume when the minimum detectable machine reading is 1×10^{-9} atm · cm^3/s of helium ($\sim 3.7 \times 10^{-10}$ atm · cm^3/s air equivalent) and for the maximum detectable leak rate if all specimens are measured within a dwell time of 1000 s. So

$R_{\min} = 1 \times 10^{-9}$ atm · cm^3/s helium,
$L_{\min} = 2.7 \times 10^{-8}$ atm · cm^3/s helium,
$V = 0.01$ cm^3,
$P_b = 5$ atm, and
$t = 1000$ s.

Thus

$$L/P_0V = 2.7 \times 10^{-6} \text{ s}^{-1}$$

so that

$$E = \sim 7 \times 10^{-3}$$

whence

$$T = \sim 1 \text{ h}$$

As the line of $E = 7 \times 10^{-3}$ intersects the 1000-s characteristic at an L/P_0V of $\sim 5 \times 10^{-3}$ s^{-1}

$L_{\max} = \sim 5 \times 10^{-5}$ atm · cm^3/s helium ($\sim 2 \times 10^{-5}$ atm · cm^3/s air equivalent)

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[8] *Semiconductor Measurement Technology*, W. Murray Bullis, Ed., Progress Report, Jan. 1 to June 30, 1975, NBS Special Publication 400-19, National Bureau of Standards, April 1976, p. 52.
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G. J. Posakony[1]

Generation of a Standards Document for an Emerging Nondestructive Evaluation Technology

REFERENCE: Posakony, G. J., "**Generation of a Standards Document for an Emerging Nondestructive Evaluation Technology,**" *Nondestructive Testing Standards—A Review, ASTM STP 624,* Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 260–268.

ABSTRACT: Nondestructive testing standards, recommended practices, specifications, procedures, definitions, and classifications are described in technical documents used by both producers and consumers. These documents provide the common language for the testing and evaluation of raw materials, products, structures, and components. Preparing technical documents which are acceptable to involved parties requires a major effort on the part of professional organizations and governmental agencies. Meeting the industrial need of maintaining pace with accepted test methods is a formidable task. Developing documents for new and evolving test methods is a challenge in technology, language, acceptance, patience, and perseverance. This article reviews the time and effort expended to develop acceptable recommended practices within the volunteer consensus mode followed by the American Society for Testing and Materials.

KEY WORDS: nondestructive tests, standards, technical writing

The term "standard" applies to any authoritative rule, principle, or measure used to determine the quality, weight, or extent of a material. In the context of this paper, the term "standards document" relates to the use of nondestructive test (NDT) methods, testing standards, recommended practices, specifications, procedures, definitions, and classifications for the testing and evaluation of materials. In the United States the authority for nondestructive evaluation (NDE) documents may come from many different professional organizations such as the American Society for Testing and Materials (ASTM), American Welding Society (AWS), American Society of Mechanical Engineers (ASME), and Society of Automotive Engineers (SAE) or from technical branches of Depart-

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ment of Defense (DOD), Department of Transportation (DOT), Nuclear Regulatory Commission (NRC), etc. The NDE standards documents may be prepared to describe general requirements for using a test method, or they may be prepared to cover a specific limited requirement for particular materials or structures. Documents may be prepared by task members of a volunteer consensus committee working with a professional organization, by consultants, or individuals working for agencies or a number of other sources.

Objective of Standards Documents

The objective of any standards document is to provide a basis for a common language between the producer and the consumer or the manufacturer and the user. Unfortunately, the NDT methods do not produce unambiguous absolute values from which the quality of a material and structure can be measured. The prominent test method such as radiography, ultrasonics, magnetic particle, dye penetrants, and eddy current produce records which are relative in nature requiring subjective judgement and human interpretation.

The innumerable variables that can occur in test instrumentation, technique, or material acceptance criteria place unusual burdens on the standards documents. The text of these documents must provide the bridge (Fig. 1) between science, technology, and application, and must be built on technical language that can be interpreted by the producer and the consumer. Interpretation of standards documents requires dialogue to relate the document to specific application, consequently the language of text and the technological base for the text are of paramount importance.

A continued upgrading is required to maintain pace with the technological advances and with changes associated with new types of materials or new uses for existing materials. Maintaining pace with the standards documents for accepted NDT methods is a monumental task. Development of standards documents for new or emerging NDT methods is a challenge in technical language and interpretation, patience, and perserverence.

Evolving NDE Standards Documents in ASTM

ASTM develops voluntary consensus standards for materials, products, systems, and services. This professional organization has nearly 150 committees and nearly 1000 subcommittees working on the preparation of standards documents.

ASTM Committee E-7 on Nondestructive Testing has subcomittees covering:

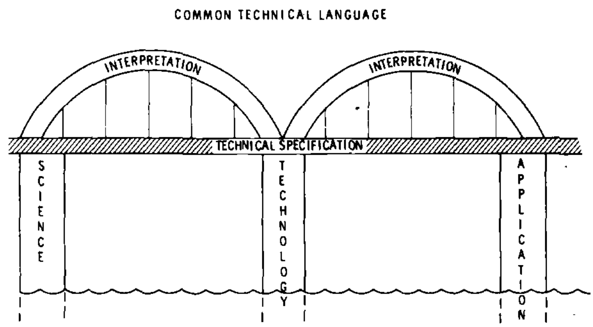

FIG. 1—*Science, technology, and application bridge.*

E07.01 Radiographic Practice and Penetrameters
E07.02 Reference Radiographs
E07.03 Magnetic Particle and Penentrant Testing
E07.04 Acoustic Emission
E07.05 Neutron Radiography
E07.06 Ultrasonic Testing Procedure
E07.07 Electromagnetic Methods
E07.08 Leak Testing
E07.09 Materials Inspection and Testing Laboratories

In addition to these subcommittees, ASTM Subcommittee E07.98 on New Methods Review is charged with reviewing emerging test methods or techniques and making recommendations to the ASTM Committee E-7 Executive Committee describing action that should be taken to ensure that meaningful standards documents will be available on a timely basis to fulfill the producer-consumer needs.

Working Through ASTM

In ASTM, a task group of a section within a subcommittee is responsible for the generation of the text of the standards documents. Once generated, the document must be approved by the entire section, then sent to subcommittee ballot. But the initital section approval is often a long hard struggle over language, punctuation, interpretation, and phraseology. A single unresolved negative vote by any member can cause the document to be returned to the section for modification or redraft. Changes in language of an editorial nature may be handled by the section or subcommittee chairman. Once clearing the hurdles of the subcommittee, the text then must be approved by the entire committee. Again, unresolved negative votes by any committee member will prevent approval of the document, and it will be returned to subcommittee and section for redraft or revision. Even after approval by the entire committee, the document still must be approved by the ASTM membership before it is published as an ASTM document. Each existing document must be reevaluated on a three-year cycle to determine if the content remains applicable, if revisions must be made, or if it is to be maintained as a working document of ASTM.

The volunteer consensus committee approach is a difficult means for generating a standards document but once established does provide an excellent base for interpretation of technologically complex tests.

Documentation for Emerging Technology

Two of ASTM Committee E-7 subcommittees, Neutron Radiography (E07.05) and Acoustic Emission (E07.04) have been added within the past five years. The Executive Committee of ASTM Committee E-7 determined that these test methods had matured to a level that standards documents would benefit the industrial need. But it takes time to generate acceptable documents within the volunteer consensus committee mode followed by all ASTM efforts.

A review of the committee activities of ASTM Subcommittee E07.04 provides some understanding of what it takes to develop standards documents for an emerging technology. Figure 2 shows the organization chart

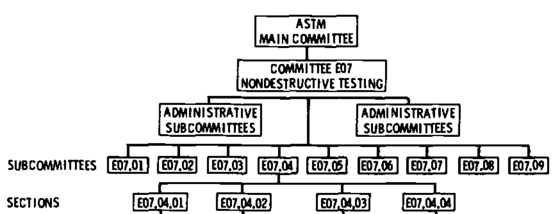

FIG. 2—*Block diagram of ASTM Committee E-7.*

for ASTM Subcommittee E07.04 and its relationship to other subcommittees. Documents must start at the bottom and work to the top. At any level the documents may be returned to the subcommittee for revision, modification, or clarification.

Acoustic Emission Background Development

Acoustic emission (AE) is new as test methods go. The phenomenon is described as the spontaneous release of elastic energy which occurs when materials undergo plastic deformation or fracture, or both. The first comprehensive investigations in AE were by J. Kaiser in 1950,[2] but only during the last decade has the phenomenon been developed for the laboratory and field evaluation of material failure responses.[3] Through the 1966 to 1970 period, the phenomenon was studied by many researchers.

In 1967, scientists working in the field established a nonaffiliated organization known as the Acoustic Emission Working Group to provide a vehicle for technical exchange of information relating to acoustic emission. From an initial group of 12, this organization has grown to exceed 200 members who continue to meet periodically to report on the research and application of AE. By 1970, research instrumentation to detect and record AE data was becoming available commercially, and many research dollars were being expended to determine effective means for using the phenomenon.

ASTM Subcommittee E07.04

In late 1971, a recommendation was made to the Executive Committee of ASTM Committee E-7 that standards documents be developed for AE test methods. Following the January Winter Meeting (1972) a new subcommittee, E07.04 on Acoustic Emission, was established. Ralph Turner, then chairman of ASTM Committee E-7, invited J. C. Spanner to chair the new subcommittee and gave Mr. Spanner the responsibility for developing the sections that would prepare the ASTM documents for the AE technology.

Working through the vehicle of questionnaires, Mr. Spanner solicited help from members and nonmembers of ASTM. (ASTM membership is not required for subcommittee activities.) The first official ASTM Subcommittee E07.04 meeting was held in June 1972. The organization and charter of the subcommittee were established, and by Jan. 1973, the committee work had been divided into four working sections:

E07.04.01 AE Terminology
E07.04.02 AE Sensors
E07.04.03 AE Instrumentation
E07.04.04 AE Application

The cross section of members of the committee included scientists and engineers with expertise in instrumentation, materials, structural design, physical acoustics, failure mechanisms, and fracture mechanics. With the qualification and experience of the task team members, it would appear that the development of text materials would be a relatively easy job. By June 1973, the subcommittee had progressed through the shakedown

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stages and text topics had been selected and the sections began the preparation work.

The Terminology Section selected two text topics

A. Glossary of AE Terminology
B. Recommended Practice on Accepted Notations for AE Results

The Sensor Section selected two text topics

A. Recommended Practice for Mounting Acoustic Emission Contact Sensors
B. Recommended Practice for Calibrating Frequency Response of AE Sensors

The Instrumentation Section selected three text topics

A. Recommended Practice for Assuring the Performance of Single Channel AE Counting Systems
B. Recommended Practice for the Calibration of AE Systems Required for Detection and Location Analysis
C. Recommended Practice for Displaying of Acoustic Emission Signals and Data

The Applications Section chose four text topics

A. Recommended Practice for Acoustic Emission Monitoring of Structures During Controlled Stimulation
B. Recommended Practice for Continuous Monitoring of Pressure Vessels by Acoustic Emission Techniques
C. Recommended Practice for Characterization of the Acoustic Emission Response from Engineering Material
D. Recommended Practice for Monitoring Structural Integrity by Acoustic Emission

Status of AE Documentation, Jan. 1976

A status review of the documents in preparation as of Jan. 1976 is presented in the following sections.

Section E07.04.01 on Glossary

By the 1974 Winter Meeting, progress had been made in many areas but only the initial "Glossary of Terms" was ready for section and subcommittee review. However, a review of the glossary text revealed gross differences in terms used by the various researchers to describe specific phenomenon. Even in the short decade of the test method, terms such as AE events, AE energy, AE signature, sensor, transducer, spectrum, count rate, and others had come to mean different things to different technical people. It took until the summer of 1975 to get consensus section agreement of fifteen terms. However, when the document was submitted for ASTM Subcommittee E07.04 ballot, several new terms were added and negative ballots caused the glossary to be returned to the section for further work and section ballet. The result is that today we have no accepted glossary for AE terminology. The revised glossary is scheduled for subcommittee ballot by the 1977 Winter Meeting.

Section E07.02 on Sensors

A fourth draft of the ASTM Recommended Practice for Mounting Acoustic Emission Contact Sensors with editorial changes was approved at the 1976 Summer Meeting and sent to subcommittee ballot.

A revised second draft of ASTM Recommended Practice for Calibrating Frequency Response of AE Sensors was sent to subcommittee ballot following the 1976 Summer Meeting.

Section E07.03 on Instrumentation

A fourth draft of ASTM Recommended Practice for Assuring the Performance of Single Channel AE Counting System, as revised, was sent to subcommittee following the 1976 Summer Meeting.

A second draft of ASTM Recommended Practice for the Calibration of AE System required for Detection and Location Analysis remains in section review and is scheduled for further revisions by the 1977 Winter Meeting.

Section E07.04 on Application

One document, the ASTM Acoustic Emission Monitoring of Structures During Controlled Stimulation with editorial changes, was approved by ASTM Subcommittee E07.04 and ASTM Committee E-7 at the Winter Meeting 1976. The document, (E 569-76), is now an official ASTM Recommended Practice for Acoustic Emission Monitoring of Structures During Controlled Stimulation and has become the first official ASTM document in acoustic emission.

From the starting date to completion and publishing of the first official ASTM document in this evolving technology has been over four years. The manhours required in preparation, editing, revising, and interpretation of technical language is staggering. The number of hours required to provide sentence structure which has common meaning to the cross section of technical people is difficult to imagine. Views of all members and their companies must be considered, and the language must be accurate to assure a common interpretation.

Time Element

It is not easy to generate an ASTM document. Four years seems to be a long time to produce a single document. Unfortunately, very few companies recognize the need to dedicate *time* to the generation of standards documents which are to become the basis for procurement, quality control, quality assurance, or the law of the land. Most committees are made up of members who often use their personal time in evenings and weekends to perform committee work. The dedication to the professional organization task is great, but time remains precious. The response time of four years or more for a new document in ASTM is not unusual. For an emerging technology such as acoustic emission it must be expected. This time cycle can be and should be reduced; however, to gain improvements will require that companies become involved in the standards documents preparation and devote more time and money to getting the job done.

Other Standards Documents in Acoustic Emission

The problem of time is not unique to ASTM. ASME took over three years to prepare its document, Proposed Standard for Acoustic Emission Examination During Application of Pressure. The text, available through ASME headquarters, is *not an official ASME document* and presently is intended as a trial text to assess some of the operational limits of this emerging technology.

Other Emerging Technologies

Acoustic emission and neutron radiography are but two of the emerging technologies of the growing NDT methods or techniques. Others, such as acoustic holography, microwave, infrared, sonic, and acoustic signature analysis have yet to be addressed by ASTM or other specification writing bodies. The current appraisal remains that the industrial need for standards documents in these areas does not yet exist. As the need arises, so will the documents.

Concluding Remarks

Nondestructive test standards, recommended practices, procedures, specifications, and such are vital links in establishing the quality or serviceability of materials, structures, and products. Many highly qualified individuals have worked long and hard to generate the documents that exist. Still there is a need to develop better means for communicating and implementing the standards documents. Time plays an important role.

Much of the problem relates to the nature of the NDT technology. Test data or records cannot provide absolute values from which judgements can be reached. Experience often provides the necessary interpretation of describing relevance of the test data. The sensitivity of the test instrument, the type of radiographic film, the nature or response of the material, etc. must be factored into the interpretation.

To be meaningful and effective, standards documents for NDT must be prepared by technical people qualified in particular disciplines. This means simply top qualified people. Since both the producer and consumer are affected, it is incumbent on all parties to be or become involved. Involvement means time and money. Few companies have been willing to commit the resources necessary to shorten the time and improve the quality and interpretability of the documents they must live by. Many companies do spend money to send their staff members to national meetings to attend working sessions such as ASTM or ASME, but a greater commitment is needed to provide the staff time and company resources to aid in the generation of documents. What is needed are more forward-looking companies who will recognize the need and place greater emphasis on the requirements for control documents which are technologically correct, effective, and timely.

E. T. Wessel[1]

Fracture Mechanics and the Need for Quantitative Nondestructive Measurements

REFERENCE: Wessel, E. T., "**Fracture Mechanics and the Need for Quantitative Nondestructive Measurements,**" *Nondestructive Testing Standards—A Review, ASTM STP 624*, Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 269–294.

ABSTRACT: Fracture mechanics technology provides a modern, systems-type, engineering approach for dealing with all of the factors involved in structural reliability. The relationships between material properties, stresses, defects, nondestructive inspection, fabrication, and structural performance requirements can be analyzed and their combined effect on structural integrity can be determined. The philosophy and general approaches for applying the technology are described. Emphasis is devoted to illustrating the vital role of nondestructive inspection in the utilization of fracture mechanics technology, and the need for quantitative nondestructive measurements is described.

KEY WORDS: nondestructive tests, standards, fracture strength

Fracture mechanics technology provides a modern engineering tool for dealing with all the various factors involved in the structural reliability of equipment or components. It is a systems approach to establishing the relationships between material properties, stresses, defects, geometry, fabrication, inspection, loading conditions, and operational requirements and their combined effects on the structural performance of a product. Being a systems approach to structural reliability, it leads people working in these various areas or disciplines to work together as a team. Herein lies one of the major attributes of using this technology. At present the technology is limited to those situations where the presence of a crack or crack-like defect either is assumed or known initially to exist or develop in service. Except for some specific situations, the assumption of a crack or crack-like defect (on a macro or microscopic scale) is quite

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realistic. Hence, quantitative nondestructive measurements constitute a vital part of any fracture mechanics analysis.

During recent years, fracture mechanics technology has advanced to a point where it now provides a sound basis for establishing practical engineering procedures for the prevention of structural failures. With appropriate information in the areas of material properties, stresses, and defects, the concepts and expressions of fracture mechanics can be employed to develop step-by-step procedures that will assure the desired degree of immunity from fracture in the structural performance of the product. The entire spectrum, from initial design and selection of materials to the end of useful service life, can be encompassed in these considerations. These same considerations also provide designers, materials, manufacturing, quality control, nondestructive inspection, and product reliability engineers with quantitative tools for tailoring the design, material, manufacturing, and nondestructive inspection requirements to the specific needs of the product.

General approaches for applying the technology are discussed. The first approach illustrates a parametric method of evaluating the trade-off between the pertinent parameters of material behavior, stresses, defects, inspection requirements, nondestructive capabilities, etc., and subsequently arriving at optimum conditions. A second general approach that facilitates a reliability analysis of any specific cracked body also is described. Both approaches also can be employed to establish the compatibility of the materials, design, fabrication, and nondestructive inspection procedures relative to ensuring the structural integrity of the component.

The intent of this paper is to introduce some of the general concepts, philosophy, and methods of employing the technology in evaluating or ensuring structural integrity and to illustrate the important role of nondestructive testing (NDT). The areas and types of information that are essential to any structural integrity analysis are described, as well as how this information may be obtained. Particular emphasis is devoted to illustrating the vital role of nondestructive inspection technology in the application of fracture mechanics and the need for quantitative NDT. The applicability of existing nondestructive technology as well as some of the current limitations and need for improved NDT methods also is addressed.

Review of Background Required for Applying Fracture Mechanics

Before proceeding to describe some general approaches for the application of the technology, it is desirable to review first some of the necessary preliminary aspects.

Remember that the technology is an interdisciplinary or systems-type approach to the prevention of failures (Fig. 1). Being interdisciplinary

FRACTURE MECHANICS:

- A Systems Approach to Establishing the Relationships between
  - Material Properties
  - Stresses
  - Defects
  - Geometry
  - Loading Conditions
  - Operational Requirements
- And their Combined Effect on Structural Integrity

FIG. 1—*Fracture mechanics systems approach.*

in nature, many activity areas and types of engineering are involved. In the laboratory, the technology development involves such areas as theoretical and applied mechanics, continuum mechanics, stress analysis, metallurgy, fractography, materials testing, physical chemistry, and nondestructive inspection. The successful application in the field requires the cooperative efforts of stress analysts, designers, materials engineers, manufacturing engineers, nondestructive inspection and quality control engineers and product integrity or reliability engineers. One of the most important attributes of fracture mechanics is that it greatly increases assurance that some important aspect will not be overlooked.

Acquiring Necessary Information

Before one can attack a practical problem, it is essential to accumulate the pertinent information in the areas depicted by the fracture mechanics triangle (Fig. 2). A detailed description of the various considerations involved in each of these pertinent areas may be found in the literature [*1*].[2] While a complete understanding of the intimate details is not essential for the purposes of this paper, a few of the salient points are discussed next.

Stress Intensity Factors—The linear elastic fracture mechanics approach to the prevention of structural failures is basically a stress intensity consideration in which criteria are established for fracture instability in the presence of a crack. Consequently, a basic assumption in employing the technology is that a crack or crack-like defect exists in the structure. The essence of the approach is to relate the stress field developed in the vicinity of the crack tip to the applied nominal stress on the structure, the material properties, and the size of defect necessary to cause failure.

The elastic stress field in the near vicinity of a crack tip in any cracked body can be described by a single term parameter designated as the stress intensity factor K [*2-4*] as depicted in Fig. 3. The magnitude of this stress intensity factor, in turn, is dependent upon the geometry of the body containing the crack, the size and location of the crack, and the distribution and magnitude of the external loads on the body. The

[2] The italic numbers in brackets refer to the list of references appended to this paper.

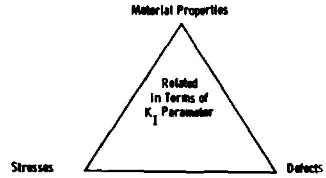

FIG. 2—*Areas of information required in the utilization of fracture mechanics technology.*

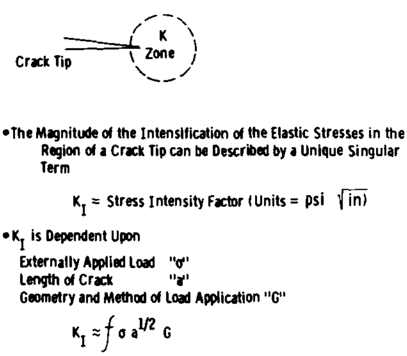

FIG. 3—*Basis of fracture mechanics concepts.*

relationship between the stress intensity factor and the pertinent external variables has been established for many structural configurations, and this relationship is normally called a stress intensity or *K* expression.

A basic requirement for the proper utilization of fracture mechanics technology is the selection of a *K* expression which appropriately relates the material parameters, stresses, and defect information. The *K* expression must model adequately the component-defect geometry and loading conditions of interest. Currently, a large number of *K* solutions are available which can be used to model a great many geometrical configurations and the number of available solutions for more complex situations is increasing gradually [5,6]. Expressions for complex loading and mixed-mode loading situations are also available in the literature. The development of sophisticated computer techniques greatly enhance the capability of deriving *K* expressions for nearly any complex situations of geometry that may be encountered in your considerations. Thus, if you are unable to find an existing *K* solution that models your cracked-body geometry of interest, the more sophisticated tools and techniques that are available already can be employed to develop the *K* solution of interest. For most cases that you may encounter, an existing *K* solution should be satisfactory to model your situation. Only in very unusual and critical situations may it be necessary to derive a new, exact, *K* expression.

Material Properties—One corner of the triangle deals with material parameters expressed in terms of K. Depending upon the particular application, it is necessary to have certain critical material parameters for toughness and crack growth. These pertinent material parameters are summarized in Fig. 4. Remember that the K_{Ic} fracture toughness criterion is only applicable to the linear-elastic (plane-strain) loading conditions.

- K_{Ic} = Critical Value of K_I at which Crack Instability Occurs - a Material Constant
- K_{Iscc} = Threshold Level of K_I below which Stress Corrosion Cracking will not Occur - a Constant for a given Material and Environment
- da/dN vs ΔK_I = Crack Growth Rate as a Function of ΔK_I Under Cyclic Loading
- ΔK_{Ith} = Threshold Level of ΔK for Fatigue Crack Growth
- da/dt vs K_I = Crack Growth Rate as a Function of K_I Under Sustained Loading

FIG. 4—*Important fracture mechanics material parameters.*

For elastic-plastic or general yield type loading situations, some other fracture toughness criteria such as J_{Ic} [2] or crack opening displacement (COD) should be employed in a manner analogous to K_{Ic} (see Fig. 5). If there is a possibility that the component will be operating in a potentially hostile environment, it also will be necessary to know the K_{Iscc} threshold for onset of stress-corrosion type of crack propagation mechanism. In

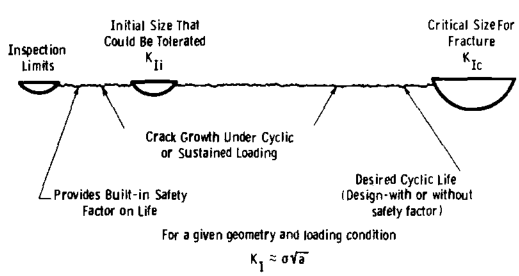

FIG. 5—*Schematic: various defect sizes of concern in fracture mechanics analysis.*

many cases, this parameter rather than K_{Ic} must be used to establish end-of-useful service life conditions as illustrated in Fig. 6. For cyclic-loaded applications, it is necessary to have appropriate crack growth rate data in the form of da/dN versus ΔK. The important parameters are C_0 and n in the basic crack growth rate expression [$da/dN = C_0 (\Delta K)^n$]. For very long cyclic life ($\approx 10^8$ to 10^{12} cycles) type applications, it is necessary to ensure that the stresses and defect sizes are controlled so that the applied ΔK level never exceeds the fatigue crack propagation threshold, ΔK_{th} (Fig. 7). In this case, one must know the ΔK_{th} for the specific material and loading conditions involved.

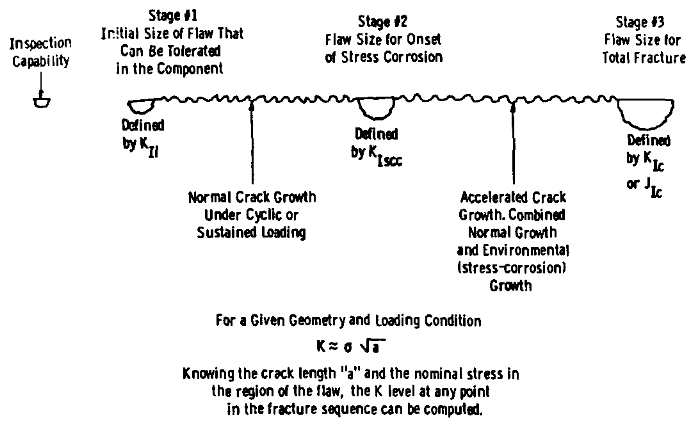

FIG. 6—*Schematic representation of the stages of fracture and the various defect sizes involved.*

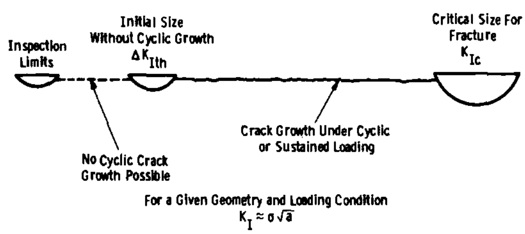

FIG. 7—*Schematic: various defect sizes of concern in fracture mechanics analysis of long life application.*

In judging the suitability of available material parameter data, or in planning tests to acquire the necessary data, it is extremely important to recognize that certain mechanical and metallurgical variables can have a pronounced influence on the value of the material parameters. Hence, it is very important that the materials data employed in any structural reliability analyses be representative of the metallurgical condition actually existing in the hardware, as well as representative of the mechanical loading conditions and environments which the hardware will see in service.

Naturally, the preciseness with which one must know the material parameters is dependent upon how refined an analysis he is attempting to make. For first approximation purposes, it may be satisfactory to use data available in the literature (with proper consideration of its applicability). On the other hand, for some critical structural integrity analysis, it may be necessary to generate one's own material parameters under closely controlled conditions representative of the specific application. For a more detailed discussion of material parameter considerations, see Ref *1*.

Defect Characterization—Another important area of information that is necessary to a fracture mechanics structural reliability analysis is defect characterization. Some quantitative knowledge relative to the defects that are assumed or known to exist in the structure is required. A few of the more important aspects are summarized in Fig. 8 and discussed next.

- Size
- Shape
- Location
- Orientation
- Distribution
- Acuity
- Geometry
- NDI Techniques
- Inspection Periods

FIG. 8—*Defect characterization considerations.*

By considering the processing and fabrication history of the component or structure, generally it is possible to make some reasonable judgments concerning the possible types and locations of defects which are likely to be present. Prior experience with the types of defects characteristic to the particular product is also useful in making some initial judgments. Certain types of defects are common to different products, for example, massive heavy section forgings, heavy castings, formed plate, welded structures, etc.

After making some initital judgments concerning the possible types of defects, it is then necessary to acquire a quantiative characterization of the defects (the degree of quantitativeness is naturally dependent upon the intended use of the information). All of the factors such as size, shape, orientation, distribution, geometry, etc., are important. The significance of shape and locations are illustrated in Fig. 9 where the top portion deals with surface flaws and the bottom relates to internal defects. For a given applied stress and K_{Ic} fracture toughness, the infinitely long surface flaw (top left corner) is the reference standard and the critical defect depth, a, is set at unity. Going from left to right at top, it is seen that as the defect length becomes shorter, the critical depth (for a given stress and K_{Ic}) increases. A similar trend is also apparent for the internal defect as shown in the bottom series. Hence, it is seen that surface defects could be more serious than internal defects, and long shallow surface defects are more serious than semicircular ones. A difference in critical flaw depth of approximately six times prevails between the two extremes shown in Fig. 9, the long shallow flaw where $a = 1$ and the circular internal flaw where $a = 5.8$. Thus the significance of the location and shape of the defect should be readily apparent.

The distribution of defects is also important. In some applications it is

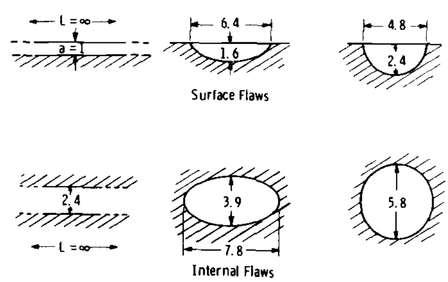

FIG. 9—*Flaw geometry for equivalent crack size effect (single cracks)* [8].

possible to have many defects in the same area, that is, clusters of nonmetallic inclusions in large forgings, porosity or foreign matter in castings and welds, craze cracking from heat treatment, branched stress corrosion cracking, etc. If the defects are close enough together so that they can interact, the effective stress intensity K can be greater than that for a single defect. The analytical methods for treating the interactions of multiple defects exist [*9,10*]. However, the nondestructive inspection capability of providing a sufficiently detailed characterization for some types of multiple defects (that is, clouds of inclusions, weld porosity, etc.) is sometimes inadequate. In the situation, the best one can do is draw an envelope around the whole cloud or cluster of defects and treat it as one singular defect. This is the conservative approach used in the *ASME Boiler and Pressure Vessel Code,* Section XI [*11*].

Other considerations involve the dimensions of the defects. All of the K expressions require some linear dimension of the defect. The orientation of the principal plane of the defect relative to the direction of principal stresses is also of significance. One aspect of the defect characterization is not important, that is, the sharpness of the edge of the defect. It always is assumed to be of a crack-like sharpness. In general, this assumption leads to some built-in conservatism in fracture mechanics analyses.

The proper characterization of defects generally involves the use of one or more of the available techniques, such as, radiography for internal defects, ultrasonics for internal defects and for depth determination of surface defects, and magnetic particle and dye penetrant techniques for surface flaw lengths. Some types and orientations of defects are found more readily by one inspection technique, and *visa versa.* Therefore, a good inspection or defect characterization process usually employs two or more of the available techniques to supplement one another. It is important to recognize that in order to derive maximum benefits from the application of fracture mechanics technology, appropriate nondestructive inspection techniques must be available and employed. For some applications, the currently available nondestructive techniques are adequate.

However, there are several areas in which better nondestructive resolution is desired, and nondestructive technology development is required before the fracture mechanics technology can be exploited fully. This aspect is addressed in more depth in the discussion section of this paper.

Stress Information—The pertinent stress information (Fig. 10) (excluding K expressions) required for use with the fracture mechanics technology can be obtained by any method of conventional stress analysis which defines the applied nominal stresses on the particular component of concern. The information required normally is computed in any design

- Magnitude
- Direction
- Mechanical, Thermal, Residual
- Stress Gradients
- Stress Concentrations
- Loading-Static and Cyclic
- Loading Spectrum
- Mixed Mode Loading
- Computer Programs

FIG. 10—*Stress and loading considerations.*

analysis. In conducting such analysis, the presence of the defect is ignored for cases where the defect is small in comparison to the size of the component. As in any stress analysis, the combined effects of mechanical, thermal, and residual stresses must be factored appropriately into the determination of the overall nominal stress. These conventionally computed nominal stresses may be used subsequently, in conjunction with an appropriate K expression for the specific cracked-body geometry of interest, to determine the crack-tip stress intensities as a function of defect sizes and the applied loads on the structure. In some cases where the defect in the component may be so large as to affect the nominal stresses, appropriate consideration must be given to modification of the nominal stress to correct for the existence of the defect. Multiplification factors for the stress intensity are available for these situations [*12*]. For complex stress fields and regions of stress gradients, such as nozzle intersections in pressure vessels, it is generally desirable to have a more intimate knowledge of the magnitude and direction of the principle stresses with relation to the size, shape, and orientation of the defect known or presumed to be present. In such cases, refined stress analysis information can be obtained readily using the sophisticated computer programs developed in recent years. Many of the general stress analysis computer programs already developed can be modified readily to handle specific situations that may be of particular concern in some crucial fracture mechanics analysis.

In addition to this type of stress information required for computation of critical defect sizes or failure conditions, similar information is required for cyclic loading. In addition to the normal mechanically applied cyclic loads, the effects of thermal or mechanical transients also must be factored into any fatigue analysis. In evaluating the structural integrity of any specific product, the various cyclic loading sequences can be laid out in block form and multiplied by the appropriate number of blocks. A simple computer program with appropriate fracture mechanics input can be used to calculate the growth of cracks involved in a typical lifetime. This technique will be illustrated later in the discussion of one of the general approaches.

General Methods of Applying Fracture Mechanics

Having developed sufficient information in all three of the critical areas (Fig. 2), one can proceed to utilize this information for establishing fracture prevention procedures that may be applied to the entire life spectrum of a product, from the initial design and selection of materials to predictions of the end of useful service life. To illustrate the general principles and procedures for applying fracture mechanics technology, we will consider two general approaches. The first of these can be developed in a parametric fashion where the relative factors of stresses, material properties, and nondestructive inspection capability can be evaluated readily and the trade-offs between these factors established easily. In addition, this approach also provides a quantitative measure of the safety factors, in terms of either stress, cyclic life, or nondestructive inspection capability. Combinations of these safety factors also can be determined. This first approach is especially applicable to preproduction situations (even before the design and material selection is fixed) and can be employed to design the desired degree of structural integrity into the product from the very beginning. While it also has applicability in other areas, this is its major attribute.

The second method is also applicable to preconstruction considerations, but is more useful in analyzing specific situations which may develop after a piece of equipment already has been built and some defects are discovered or suspected to exist. It is also more applicable to situations where the type of cyclic loading is highly variable compared to the simple constant load of cyclic loading for which the first method is most applicable. Another instance where the second approach is particularly applicable is the case where a precise K_{Ic} value is unknown, difficult to measure, or is not an appropriate fracture criteria. In some situations, a highly precise definition of the terminal conditions for total failure is not the major concern, and for this case, the second approach is best suited. The relative value of the two approaches will be better appreciated after reading the following sections.

General Parametric-Type Approach

The general approach is shown schematically in Fig. 5 in terms of the failure sequence. A semielliptical surface defect geometry is depicted. Referring to Fig. 5, we can develop the approach as follows.

The first step is to select a K stress intensity expression which best models the defect-component geometry and loading conditions of practical interest, in this case, the semielliptical surface defect. Then, knowing the defect size and nominal stress in the region of the defect, it is possible to compute the instantaneous K level at any point in the failure process.

The termination of life (fracture) will occur when the prevailing K level reaches K_{Ic}, the characteristic critical value of K where fracture instability occurs for a given material. Referring to the end point in fracture sequence in Fig. 5, if the stress for a given application and the K_{Ic} of the material is known, the critical defect size for fracture instability can be determined. In those situations where a hostile environment is present and the material is such that it is affected adversely by the environment, the end of practical useful service life may better be defined as the point where the K level reaches K_{Iscc} as shown schematically in Fig. 6. Hence, a knowledge of either K_{Ic} or K_{Iscc}, together with a knowledge of the prevailing stress, will permit a calculation of the critical defect size for end of useful service life, and appropriate nondestructive techniques can be employed to be certain such defects do not exist in the component of interest.

However, very few applications of practical interest involve only a single cycle of life. Most structures experience a period of either cyclic or sustained loading or combinations of both. In this situation, the primary interest for fracture prevention involves considerations relative to what size defect can be tolerated at the beginning of life and not grow to the critical size during the desired lifetime of the component. This subcritical crack growth phase of the fracture sequence also is shown in Figs. 5 and 6.

Fracture mechanics technology can be used to determine the rate of crack growth (under either cyclic or sustained loading) from a subcritical size to the critical size for fracture. It is then possible to determine the initial K level (K_{Ii}) which could exist at the beginning of life and just grow to the critical K(K_{Ic} or K_{Iscc}) during some specific lifetime. This K_{Ii} can be interpreted in terms of combinations of stress and defect size in the manner analogous to that employed for K_{Ic}. For the purpose of the illustrations (Figs. 5 and 6), the initial defect size that will grow to a critical size in a specified lifetime can be defined from a knowledge of the material properties and stresses. This initial defect size must be related then to the size discernible with the capability of the available nondestructive inspection techniques that are applicable to the material and component of interest. To assure reliability for the desired lifetime, it is essential that the nondestructive inspection capability and the corresponding defect size acceptance limits be on the left side of K_{Ii} (Figs. 5 and 6), that is, the K levels associated with any defects that are permitted to remain in the structure at the start of life must be such that a life in excess of the desired minimum be assured. In practical situations, it is desirable that the material selected for the application have adequate K_{Ic} fracture toughness, K_{Iscc} stress corrosion resistance and resistance to crack growth to permit the existance of flaws of a discernible size and still provide, with appropriate safety factors, the desired life and integrity in the component. Alternatively, if material with the desired characteristics is not available, the design stress levels must be reduced to a level compatible with the material parameters available, or the nondestructive procedures must be improved so that smaller defects can be found and characterized.

Thus with the proper information, we can build the type of picture illustrated in Figs. 5 through 7. The versatility of such an approach can better be appreciated by considering some actual data. A quantitative representation of the approach shown schematically in Fig. 5 is provided in Fig. 11. This is the exact same information as shown schematically, but not it is on a quantitative basis.

The data shown in Fig. 11 is for a hypothetical structure fabricated from A533 Grade B Class I steel. The measured material properties employed are: $K_{Ic} = 180$ ksi$\sqrt{\text{in.}}$ (minimum value for the application temperature range of 75 to 550°F), and the fatigue crack growth rate parameters, $C_0 = 1 \times 10^{-15}$ and $n = 2.2$, from cyclic crack growth tests. One curve is based on cycling the stress from zero stress to the maximum code allowable stress of 26 700 psi, and the second curve is for a safety factor of 1.5 times maximum code allowable or $\Delta\sigma = 40\ 000$ psi.

Data such as the example shown in Fig. 11 facilitates making quantitative judgments regarding the compatibility of the stresses, material

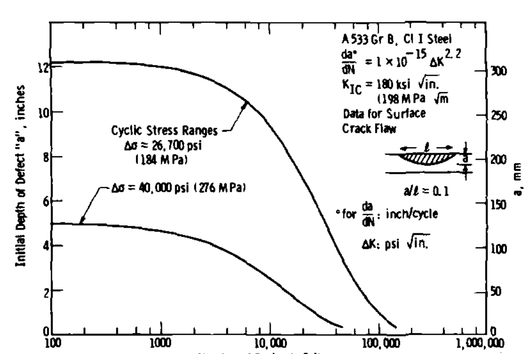

FIG. 11—*Cyclic life of A533-B steel for various initial defect depths and cyclic stress levels.*

characteristics and nondestructive inspection capabilities. For example, it is now possible to predict the cyclic life obtainable from either cyclic stress level and any initial (a_i) defect size, and to relate these to the inspection capability and desired cyclic life. Some real significance also can be attached to safety factors as well.

To illustrate the versatility of this approach, let us employ the data in Fig. 11 for the case of a hypothetical vessel where the desired cyclic life is 10 000 full pressure cycles from zero to maximum design stress anywhere in the temperature range of 75 to 500°F. Let us assume that the available nondestructive inspection techniques are proven to be capable of finding and describing any surface defect whose size is greater than 0.5 in. deep and 5 in. long. Referring to Fig. 11, the cyclic life for an initial defect 0.5 in. deep by 5 in. long is 40 000 cycles at $\Delta\sigma$ = 40 000 psi and 130 000 cycles at $\Delta\sigma$ = 26 700 psi. Thus based on cyclic operation at 26 700 psi, the safety factor on life is 13. If a safety factor of 1.5 is added on stress ($\Delta\sigma$ = 40 000 psi), the cyclic life still has a safety factor of 4. Thus it is readily apparent that safety factors can be determined on either stress or cyclic life or combinations of both. Hence, the designer can make trade-offs on these factors and emphasize that area in which he has least confidence.

Safety factors on inspection capability also can be established in a similar fashion. For example, using the same hypothetical structure just presented, assume that the maximum design stresses are set at levels which are sufficiently below maximum code allowable stress (26 700 psi) to provide a safety of 1.25 (relative to maximum code allowable). Also assume that the desired safety factor on cyclic life is 10. To establish the corresponding safety factor on inspection capability, the initial allowable defect size for the design level of approximately $\Delta\sigma$ = 21 360 psi and 100 000 cycles (safety factors included) is determined from Fig. 11 and then related to the established inspection limits, the results yielding a safety factor of approximately 2 on initial allowable defect size. Hence, the combined safety factors are 1.25 on stress, 10 on cyclic life, and 2 on inspection capability.

Thus, from the foregoing example, it is readily apparent that this approach provides a quantitative and highly versatile method of designing against failure. If, in the example just provided, it was demonstrated that the desired degree of compatibility between stresses, material properties, and inspection techniques was not satisfactory, remedial steps could be taken prior to even starting construction. Such action could take the direction to lower stresses, finding a material with better toughness and crack growth rate characteristics, and improving the inspection techniques to find smaller defects. The improvements resulting from changes in any of these factors readily could be ascertained quantitatively using the methods employed here. Optimization of the various safety factors could be continued until the desired degree of immunity from failure was achieved, and the relative safety factors on each aspect could be matched to the uncertainties associated with that item.

Specific Examples of the Application of the Parametric Approach—This parametric approach has been applied successfully to many real problems. It has been used for several purposes, for example: to evaluate trade-offs between stresses, material properties and NDTs and to optimize safety factors; to establish realistic and meaningful nondestructive procedures and associated defect acceptance standards; to establish the need for and the frequency of periodic nondestructive in-service inspections of critical components; to evaluate the remaining safe life of components where cracks had been discovered during service; to improve the effectiveness of original designs and efficient use of materials; and to establish step-by-step fracture prevention procedures. All of these applications included the pertinent nondestructive considerations involved in the various phases of construction of a component, from the quality control of initial incoming material to the final inspection of the structure before it goes into service. Some actual data for some specific examples are provided next.

Marine steam turbine casings—ASTM Specification for Corrosion-Resistant Iron-Chromium, Iron-Chromium-Nickel, and Nickel Base Alloy Castings for General Application (A 296-76), 12Cr steel castings are used in some marine steam turbine castings. Specific types of defects are inherent in the manufacture of large steel castings. Considerable time and money was spent inspecting, machining-out defects, repair welding, reinspecting, rerepairing, and reheat treating in order finally to produce an essentially defect-free casing. A fracture mechanics analysis was conducted with the objective of evaluating the severity of various types of defects and ultimately establishing safe, realistic standards for acceptance of defects.

A typical example of the type of data generated in this analysis is shown in Fig. 12. The fracture toughness (K_{Ic}) of this material was so high that it was proven that the critical defect size to cause failure was extremely large; in fact, a defect size greater than the casing wall thickness could be tolerated without causing a catastrophic failure of the casing. Hence a leak-before-break situation prevailed. The parametric curves in Fig. 12, therefore, were based on the amount of cyclic flaw growth required to cause a leak rather than a catastrophic rupture. By relating the information shown in Fig. 12 to different regions of the casting where different stresses prevailed (and where different types and sizes of inherent defects existed), it was possible to establish safe and realistic standards for defect acceptance. These standards were employed in conjunction with appropriate nondestructive methods and procedures to decide which defects had to be removed and which could be left in the castings without

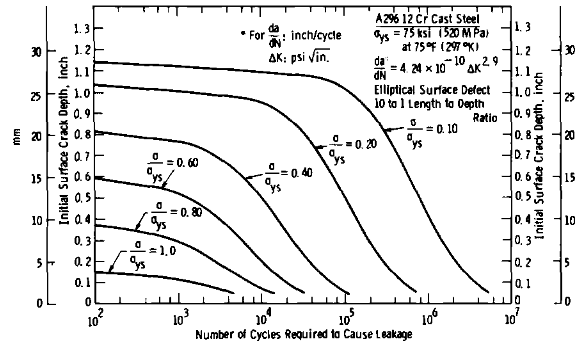

FIG. 12—*Cyclic life curves for ASTM Specification A 296-76 12Cr turbine cylinder cover castings.*

impairing the structural integrity of the casing. The overall results affected considerable savings in time and money by eliminating the need for much of the repair welding and related aspects of inspection, rerepairs, reheat treatment, etc.; the final integrity of the casting was as good, if not better, than those previously consisting of a massive amount of repair welds. A similar approach has been utilized for large castings used in other applications such as large stationary steam turbines as reported by Clark [*13*].

Pressure vessel used in a seawater environment—Another example involved a pressure chamber intended for use in a seawater environment. Pertinent data are shown in Figs. 13 and 14. The curves in Fig. 13 are based on the end of life being governed by the K_{Ic} fracture toughness or the terminal point in the schematic diagram of Fig. 5. However, in order to provide some extra conservatism and positive assurance of structural reliability a similar set of curves (Fig. 14) were developed based on end of useful service life being governed by K_{Iscc} (see Fig. 6). By com-

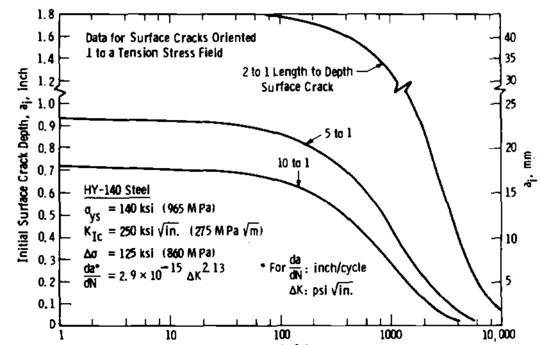

FIG. 13—*Cyclic life data for a pressure chamber based on* K_{Ic}.

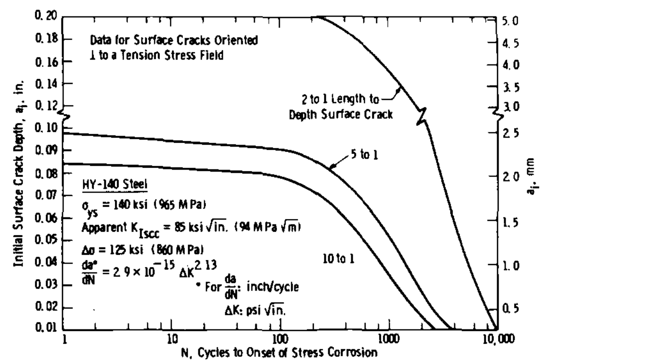

FIG. 14—*Cyclic life data for a pressure chamber based on apparent* K_{Iscc}.

paring the initial defect sizes in Figs. 13 and 14, it is apparent that the use of K_{Iscc} results in the need for more stringent and quantitative nondestructive procedures. Because of the relatively small size of the defects of interest in this application it was decided that a periodic in-service nondestructive inspection would be conducted every 100 cycles to ensure that no flaws with an applied K level in excess of K_{Iscc} could ever exist in the vessel.

Application using 7079-T6 aluminum—A final example involved the use of a high strength aluminum alloy (7079-T6) in a cyclic loaded application. The parametric curves are given in Fig. 15, and an example of the translation of these data into a form of direct value to establishing acceptable defects (in terms of depth and length) is provided in Fig. 16. Information presented in this form then can be used readily for establishing appropriate nondestructive procedures and quality control specifications. Details concerning this example may be found in the literature [*14*].

General Method Based on Accumulated Crack Growth

There is another general method of applying fracture mechanics technology which is applicable both to preconstruction considerations and to analyses of specific situations which may develop subsequently. This approach is illustrated schematically in Fig. 17. Basically, the concept is to start with an assumed given initial defect size (based on inspection capability or proof test), add all of the crack growth which would occur for a given type and number of cycles of loading, and then compare the defect size or K level prevailing at the end of the specified service life with the critical size for failure. The stress intensity factor K (where $K \approx \sigma\sqrt{a}$) can be used equally as well as defect size to describe the initial starting, end of specified service, and critical conditions. Using this approach, safety factors can be determined on the basis of stress intensity factors, defect sizes, and cyclic life, or combinations thereof.

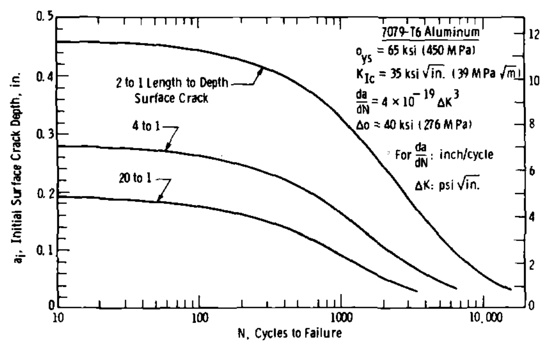

FIG. 15—*Influence of flaw geometry on cyclic life* [14].

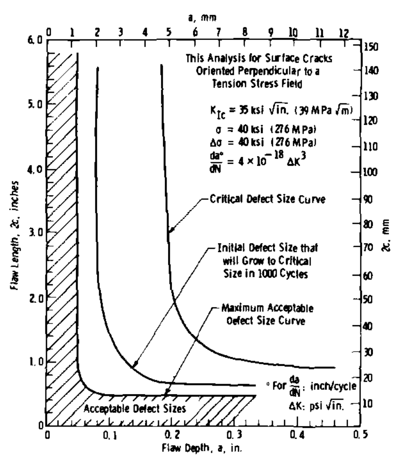

FIG. 16—*Acceptable flaw size and shape curve* [14].

There are some situations where this approach offers some advantages over the general cyclic life type approach illustrated in Figs. 5 and 6. One of these is the situation where the type of cyclic loading which a component experiences is variable compared to the simple constant load type of cyclic loading used in the construction of Fig. 5. Starting with an assumed defect size based on limits of nondestructive inspection, one can compute the amount of crack growth associated with the various loading which the component is expected to encounter. Effectively, the crack growth associated with each cycle of loading is added to the previous crack size, and a new growth rate representative of the ΔK for the next cycle ($\Delta K \approx \Delta\sigma\sqrt{a}$) is employed to compute the next increment of crack growth. This process is repeated then over and over again until the total crack growth has been integrated over the total lifetime. In practice it generally is not treated as an individual cycle basis, but several cycles of a given type and stress range generally are lumped together to determine

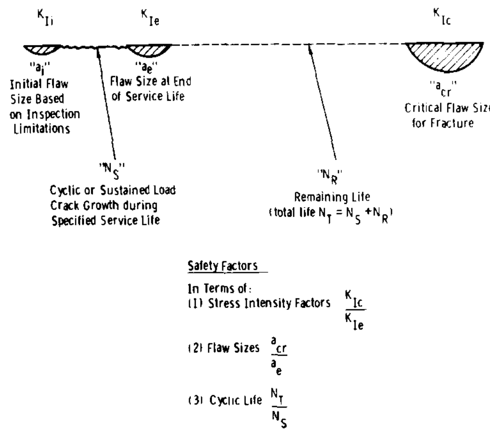

FIG. 17—*Fracture mechanics approach to failure prevention.*

the crack growth over some increment of service life; then this process is repeated for different type cycles, load ranges, and time periods. Computer programs can be written readily to handle these computations once a realistic representative cyclic spectrum is defined. A good example of the use of this type approach for complex cyclic loading is described in a paper by Mager on nuclear pressure vessels [*15*].

Another instance where this second approach is particularly applicable is the case where a precise measurement of K_{Ic} is either difficult or cannot be measured in the section thicknesses and materials of specific interest, that is, where plane-strain conditions do not exist. In this latter case, the critical K level or defect size will have to be defined by empirical methods and less accuracy of definition accepted. If the critical condition so defined (empirically) is quite remote from the condition which is expected for end of service life (Fig. 17), then a less accurate definition of the critical condition may be quite satisfactory for engineering purposes. This latter aspect now is capable of being handled by several approaches, that is, J_{Ic} for elastic-plastic loading conditions [*7*]. If, on the other hand, the critical condition cannot be approximated reasonably well or the difference between end of life and critical does not provide adequate assurance against failure, then corrective steps must be taken to achieve a satisfactory condition. These steps may take the direction of improving inspection limits, lowering stresses by design or operation, obtaining improved material with a greater tolerance for defects, or getting a more precise method of defining the final critical conditions.

General Areas where Fracture Mechanics is being Employed

To supplement the few specific examples described previously, a few remarks regarding the general areas of application (Fig. 18) are provided next.

Evaluation of Equipment Found to Contain Defects

One of the major areas in which the technology has proven to be quite useful is in the evaluating the structural integrity of major pieces of equipment after some cracks had been discovered. Naturally, when a crack first is discovered in some critical piece of equipment, the major question is concerned with the possible degradation of structural integrity. Prior to the development of fracture mechanics technology, a quantitative evaluation of the effects of a crack on the structural integrity of a piece of equipment was not possible, and the resulting decisions took one of the following directions: remove the defect, repair the unit to eliminate the defect, or replace the equipment. Quite often any one or combination of these solutions was impractical or impossible. However, now by the intelligent application of fracture mechanics technology, it is possible to make a quantitative assessment of the situation and decide on an appropriate course of action to safeguard the system and still derive maximum utilization of the equipment.

Establishment of Realistic Nondestructive Inspection Standards for Defects

Another area in which the fracture mechanics technology is being employed, and in which the potential benefits are extremely large, is establishing realistic standards for defect acceptance. Most inspection or defect acceptance standards currently in existence are based on "bestworkmanship," that is, the standards represent the best one can expect from the product and the available nondestructive inspection techniques. Down through the years, as the workmanship improved in terms of less defects and improved methods for finding defects, the standards were made correspondingly more rigid. In most cases of interest, the current standards tend to be too severe or unrealistically conservative. However, there are also a few cases where the existing standards were not restrictive enough. In either event, fracture mechanics was employed to establish

- Structure Reliability Evaluations of Hardware Containing Cracks
- Establishing Realistic Standards for Defect Acceptance and Inspection
- Demonstration of Structural Integrity or Safety
- Failure Analysis and Associated Remedial Action
- Improved Useage of Materials
- More Efficient and Effective Designs
- Establishment of Failure Prevention Procedures

FIG. 18—*Major areas of application of fracture mechanics technology.*

realistic standards for inspection and defect acceptance that are based on sound engineering data and procedure rather than the conventional best workmanship judgment criteria. One outstanding example of the use of the technology in this area is in the *ASME Boiler and Pressure Vessel* [*11*].

Demonstration of Structural Reliability

Quite often for some very critical types of applications, an equipment manufacturer is called upon by the customer or regulatory bodies to demonstrate the safety or structural integrity of the equipment. This is particularly the case in nuclear power plant equipment. There are several examples where fracture mechanics technology has proven to be quite useful in demonstrating the structural integrity or safety equipment. Several detailed examples may be found in the literature [*1,15–18*].

Failure Analyses and Remedial Actions

Another major area where the technology is being applied is in determining the causes of structural failures and providing direction for appropriate remedial action. This area of application is particularly effective when the combined technologies of fracture mechanics and fractography are employed for failure investigations. The use of this combined technology approach is covered in detail in a paper by Bates and Clark [*19*].

In general, the use of fracture mechanics in failure analyses can be very helpful in identifying the cause of the failure. For example, was there some abnormal deficiency in the material properties, what were the actual loading conditions relative to the anticipated design conditions, was there some defect of an abnormal size; or was there some combination of adverse factors involved? In answering these types of questions, the failure investigation usually involves the following sequence of events. A thorough fractographic and metallographic examination is made to pinpoint the origin and nature of the failure, as well as to characterize the metallurgical features of the material. The pertinent fracture mechanics material parameters of interest are determined from specimens taken from the failed component. The results of these material tests then are used in conjunction with the anticipated or design loading conditions to predict the performance anticipated in the structure for the defect conditions observed from the fractographic studies. These results can be compared then to the actual performance and failure conditions. Any discrepencies between the predicted and actual performance can be evaluated then in terms of possible material deficiencies, higher stresses then anticipated, or the existence (or development in service) of defects in excess of tolerable sizes. Once the primary contributing factor, or combined factors, have been identified, the direction for remedial action can be determined. This could take the form of improving the material properties, lowering the stresses, or improving the fabrication and nondestructive inspection procedures so that intolerable defects can be eliminated.

Improved Usage of Materials

The fracture mechanics technology has provided a powerful new tool for the more efficient and effective use of materials in that it provides a much more in-depth intelligence about the load-bearing capability of the materials under actual required structural performance conditions. With this increased knowledge about the materials response to loading under real conditions, we are learning how to extract the maximum performance from the available materials and thereby optimize their usage. For example, in the past in situations where a high degree of immunity from brittle fracture was desired, we generally bought as much fracture toughness as we could get in a material. Quite often we had to pay a premium price to get this toughness. Now, using fracture mechanics, we can determine much more quantitatively just what degree of toughness is required and buy only that which we need. Conversely, in our desire to reduce costs we sometimes go to extremes and buy a cheaper material than is really required. The technology now available enables us to decide just what quality level is required to achieve the desired degree of immunity from structural failures. This rationale is not confined to fracture toughness considerations, but can be used in an analogous fashion to evaluate and optimize the most important parameters of concern in the application, that is, yield strength, resistance to fatigue crack initiation or propagation, stress corrosion susceptibility, fatigue crack growth threshold, etc.

Improved Designs

When the technology is employed (especially in conjunction with the material optimization techniques just described) to design considerations, it can be a powerful new tool to promote more effective and efficient design. In essence, it takes out many of the ignorance factors and permits a much more quantitative evaluation of the safety factors required as seen from previous sections. It allows the designer to make parametric studies of the possible tradeoffs in the various areas, and thus optimize this design more effectively. When used in conjunction with the new sophisticated computerized tools for stress analysis, today's designer has available to him engineering tools which are an order of magnitude improvement than those he had 10 or 15 years ago.

In many areas the designers are beginning to use these new tools to good advantage. For example, the past trend to demand higher and higher strength materials is being reversed. Now with the use of fracture technology, it is possible to evaluate the tradeoffs quantitatively between strength and fracture resistance and arrive at an optimum design situation. In general, it has been discovered that improved structural reliability can be obtained by using lower strength materials and stressing them to a higher percentage of their yield strength, rather than using a higher strength material and the same level of stress. In essence, this means giving up some of the old margins of safety against ductile overload failure to gain an improved margin of safety against brittle failure. Until recently this balance has been weighted very heavily in favor of protecting against plastic overload. However, with the increased knowledge available from the development of fracture mechanics technology, this trend is being reversed and a more reasonable balance between the two competitive modes of structural failure is being established. The electrical equipment manufacturers are among the leaders in this trend to a more modern design philosophy.

Summary of Areas of Applications

There are innumerable examples of where companies have employed the overall technology to good advantage. These encompass a broad area of materials and applications ranging from the very heavy electrical power-generation equipment involved in turbines, generators, nuclear power plants, etc., to small low-cost, high-volume components in consumer products. Similarily the purposes for which the technology has been employed is also broad; some of the major areas involve: establishment of realistic inspection standards and corresponding nondestructive procedures; material evaluation, selection, and specifications; improved designs; life expectancy, and structural reliability analyses of hardware suspected or known to contain cracks or crack-life defects; failure analyses and definition of required corrective actions; analyses of effects of postulated accident conditions on structural integrity; failure probability analyses; and various other purposes.

While the technology has been employed gainfully for the purposes described in this paper, the primary intended use of the technology is to prevent structural failures and, at the same time, promote more effective designs and more efficient use of materials. Here in lies the singular, most significant contribution which the technology can make.

Discussion

As seen from the preceding portions of this paper, fracture mechanics technology (including a vital contribution from NDT) is advanced sufficiently well to be a powerful tool for assuring structural integrity. However there is still much opportunity for improvements and refinements in all the pertinent areas (Fig. 2). One of these areas is obviously NDT. While in many situations the present state of the art in NDT is quite adequate, there are some specific areas where enhanced nondestructive capability is desired and needed, or where advanced nondestructive concepts could improve the overall value of this systems-type approach substantially to ensuring structural reliability. A few of the more obvious areas now are discussed briefly.

Improved Standards for Calibration and Use of NDT Systems

There is a recognized need for the development of industry-wide standards for calibrating and using nondestructive systems. Many of the existing standards are unique to a given industry or fraction within an industry. While the in-house standards developed for specific situations may be perfectly adequate, the lack of common standards can lead to difficulties in comparison of results between individual companies or producers and suppliers. The lack of reproducibility of NDT results between various nondestructive techniques or inspection teams has been demonstrated dramatically by several interlaboratory programs.

Improved Resolution and Defect Characterization Capability

In some critical high stressed applications where relatively high-strength and brittle materials are required, the sizes of defects of concern can be quite small. This is especially true for those situations where relatively low values of applied K or ΔK are involved. For example, a notched member with a high stress concentration and a low K_{Iscc} for the available material and the service environment. In this case the defect size that would develop an applied K level in excess of K_{Iscc} (and hence endanger reliability due to stress corrosion accelerated crack growth) could be in the order of 0.010–0.020 in. in depth. Another example where small defects are of concern is those applications where extremely long cyclic life ($\approx 10^9$ to 10^{12} cycles) is required and one must be concerned with keeping ΔK (the combined defect size and stress, $\Delta K \approx \Delta\sigma\sqrt{\pi a}$) below the threshold for fatigue crack propagation (see Fig. 7). In such cases, the ability of NDT to locate and define small defects is paramount to ensuring the desired reliability.

Characterization of Multiple Defects

One of the more serious current limitations is associated with the inability of present NDT to differentiate between different types or to describe the detailed makeup of "clusters" or "clouds" of indications. Such types of defects (clusters or clouds composed of many small defects) are of particular concern in heavy section applications such as large steel forgings and welded structures where clusters or clouds are inherent in the steel making or fabrication processes. In large forgings these may be fine nonmetallic inclusions, microcracks, or voids from the original large ingots involved. In heavy section welds the clouds could be fine porosity, entrapment of foreign material such as slag, or fine microcracks. At present, NDT in most cases will be capable of defining the location and general dimensions of the cloud. A fracture mechanics analysis will consist then of drawing an envelope around the cloud and treating it a one large single defect, such as specified in *ASME Boiler and Pressure Vessel Code* [*11*]. In most cases (especially for clouds of fine nonmetallic inclusions in large forgings) this is a very conservative approach. The life prediction based on assuming a single large continuous flaw is only a small fraction of the actual life of the component. Most of the actual life is spent in the process of initiating cracks within the cluster or cloud and in the subsequent joining up of a network of cracks to form a single continuous defect. While it is currently possible to analyze this initiation and link-up process from an analytical or experimental testing view point, it is not possible to relate these results to NDT. Hence this part of the safe life of the component and structure cannot be utilized in any quantitative fashion. Improvements in NDT which would differentiate between harmful and innoculous types of cluster or clouds would be very beneficial. Further refinements in NDT which would describe the detailed makeup of the specific types of clouds (so that the interactions between neighboring flaws could be analyzed and the link-up process could be monitored by NDT during service) would represent a dramatic technical breakthrough in improved life-prediction methodology. Hence this is a very fertile area for NDT technology development, such as, focused transducers and acoustic holography.

Acoustic Emission as an In-Service Surveillance System

Considerable effort and interest is being devoted to the use of acoustic emission as an NDT tool, especially for in-service monitoring of critical structures or components. From a fracture mechanics or structural reliability analysis point of view, the ultimate development of this NDT tool has tremendous potential. For example, if in the future it becomes possible to establish precise, quantitative correlations between some acoustic emission signature for a crack in a structure and the K or ΔK level prevailing in the region of the crack, one can then use the acoustic emission information to enter into the type of failure diagram shown schematically in Fig. 5. Once this translation is made, the precise location at that specific point in time in the failure process can be established, and the remaining life of the structure can be evaluated using the fracture mechanics approaches described earlier in the paper. Continued surveillance via acoustic emission could be used to follow the sequence of failure (Fig. 5), and ultimately to define safe limits. The key to the potential exploitation of this approach is the development of reproducible, reliable, quantitative correlations between acoustic emission and the applied K in the structure. This is another fertile area for some good collaborative development work between NDT (acoustic emission) and fracture mechanics disciplines.

Summary

Fracture mechanics technology is sufficiently well advanced to be a very powerful new tool for assuring structural reliability. It is a systems-type approach involving several discipline areas, namely, those associated with materials, stresses, and defect considerations. Nondestructive testing is an essential and vital part of the fracture mechanics systems approach. This approach can be employed gainfully in several nondestructive areas, some of which are: evaluations of the applicability or limitations of various nondestructive systems for specific applications, or both, the establishment of a sound engineering and realistic basis for defect acceptance standards and associated nondestructive procedures; the development of meaningful in-service nondestructive surveillance systems including the frequency for periodic inspections; and defining specific areas and needs for advanced nondestructive technology development. While significant progress has been made in recent years, the potential for future developments through collaborative efforts of NDT and fracture mechanics is extremely encouraging.

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Standards for Quantitative Nondestructive Examination

REFERENCE: Tittmann, B. R., Thompson, D. O., and Thomspon, R. B., "**Standards for Quantitative Nondestructive Examination,**" *Nondestructive Testing Standards—A Review, ASTM STP 624,* American Society for Testing and Materials, 1977, pp. 295–311.

ABSTRACT: In this report, the subject of ultrasonic standards is reappraised in terms of history, philosophy of calibration, and future needs. In answer to the critical need for a procedure to calibrate ultrasonic systems for quantitative nondestructive examination (NDE), a new calibration standard and procedure is proposed.

The calibration standard proposed is the far-field sphere (cavity or inclusion embedded in a solid or a ball suspended in a liquid). As a result of recent work, the sphere now is understood well theoretically and experimentally and can be reproduced and fabricated in a solid, for example, by diffusion bonding techniques. A major advantage of the sphere is that it has no preferential orientation, the transducer alignment is not critical, and it allows multipoint checks on a single standard block.

The backbone of the calibration procedure is an equation which relates the transmitter signal to the received signal in a quantitative way. With the help of this equation, the scattering parameters, namely, the angular dependence, frequency dependence, and amplitude of the differential scattering cross section may be determined from data obtained on a calibration standard. The results may be compared then with the invariant theoretical solution to verify the proper operation of the ultrasonic system. A key feature of the development is the *G*-factor which is a proposed figure of merit for a transducer. The discussion includes a technique for its simple determination and its use in the calibration procedure.

KEY WORDS: nondestructive tests, ultrasonic frequencies, standards, spheres, scattering cross sections, transducers, calibration, eigenvalues, eigenvectors, flat-bottom holes, attenuation, goniometers

History of Standards

The ultrasonic reference block is defined in American Society for Testing and Materials (ASTM) Definition of Terms Relating to Ultrasonic Testing (E 500-74) as "a block used to establish a measurement scale, and

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a means of producing a reflection of known characteristics." Many reflector shapes are used, particularly when the part to be inspected presents geometric difficulties such as in tubes, pipes, or weldments in which angle shear beam techniques commonly are employed. Included are side-drilled holes, surface notches of various shapes, and angle-drilled flat-bottom holes [ASTM Recommended Practice for Ultrasonic Contact Examination of Weldments (E 164-74), ASTM Ultrasonic Inspection of Metal Pipe and Tubing for Longitudinal Discontinuities (E 213-68(1974)), and ASTM Ultrasonic Inspection of Longitudinal and Spiral Welds of Welded Pipe and Tubing (E 273-68(1974))]. However, for the majority of inspection applications, in which normally incident longitudinal waves are used, a flat-bottom hole drilled normally from a back surface has become the universal reflector employed in standard reference blocks. The procedures recommended by ASTM for fabricating and controlling these standard reference blocks in aluminum and steel are given respectively in ASTM Recommended Practice for Fabricating and Checking Aluminum Alloy Ultrasonic Standard Reference Blocks (E 127-75) and ASTM Recommended Practice for Fabrication and Control of Steel Reference Blocks Used in Ultrasonic Inspection (E 428-71(1975)). Some of their advantages and shortcomings were reviewed recently during a panel discussion by Posakony [*1*],[2] and parts of the edited transcription of that verbal presentation are reproduced here.

> The flat bottom hole goes back to the early 1950s when there was a search for methods of setting up equipment to Air Force standards. The objective was to establish acceptance-rejection criteria for manufacturers of raw material.
>
> The flat bottom hole was the obvious choice because everybody knew how to make a flat bottom hole, and, obviously, it was a good target for a reflector. The material was carefully chosen by Alcoa as being a material that would always be available, easily reproducible, and which had the properties that we wanted. It had reproducible attenuation and velocity. The result was a block of material which has never been duplicated. Efforts to get Alcoa and/or other aluminum manufacturers to reproduce this same material have been unsuccessful, irrespective of price. (We, at times, would offer to buy 10,000 lineal feet of material, and they said, "No, that's not a big enough lot, and even if it was we couldn't guarantee the material property.").
>
> So, it really turned into a dilemma. The dilemma got worse when ASTM E-127 finally described how to make a flat bottom hole and the control limits required. Although everyone made flat bottom holes accordingly, the result was just as bad as before. Since E-127 was just a recommended practice, calling it out as a procedure in a contract did not require the manufacturer to meet the recommended ultrasonic specification. As a result, when it became evident that there were going to be large buys by the Air Force or other service organizations, all that was needed to meet the specification was to have a

[2] The italic numbers in brackets refer to the list of references appended to this paper.

caliper that was traceable to the Bureau of Standards and a drill press, and you could meet the specification. You could respond to a DoD buy order, and this did happen.

As a result there was no requirement for the ultrasonic response. I recall many times the DoD inspector would come in and would say, "Where are your calibration blocks? How do you trace this back to the Bureau of Standards? And what is ultrasonics?."

Besides this difficulty in realizing a defined, reproducible ultrasonic response with standard reference blocks, there is a second objection to the manner in which they are used. Two uses commonly are encountered. One is to evaluate such performance characteristics as linearity and sensitivity of pulse-echo systems, as specified in ASTM Recommended Practice for Evaluating Performance Characteristics of Pulse-Echo Ultrasonic Testing Systems (E 317-68). The second is to establish a measurement scale for the strength of an unknown ultrasonic reflection [ASTM Recommended Practice for Ultrasonic Pulse-Echo Straight-Beam Testing by the Contact Method (E 114-75) and ASTM Recommended Practice for Immersed Ultrasonic Testing by the Reflection Method Using Pulsed Longitudinal Waves (E 214-68(1974))]. Assuming that the reference blocks have the ultrasonic response intended in ASTM Recommended Practice E 127-75, these procedures would provide a practical method to order the reflection strengths of various ultrasonic discontinuities. However, the block-to-block variability significantly diminishes the utility of this approach. Furthermore, if quantitative information is to be derived from an ultrasonic test as described in the next section, the effects of attenuation and variabilities in other material properties must be taken into account more carefully than is possible in such a comparison procedure. A scheme to do so is outlined in the present paper.

Future Standard Needs in Quantitative Nondestructive Examination

The calibration procedures and standards that will be needed in quantitative nondestructive examination (NDE) are somewhat different from those in use today and described here because of a new philosophy of design and inspection [*2*]. For many years, structures were designed according to a zero-defects philosophy. More recently, fracture mechanics design procedures have been adopted which recognize that defects are present in any structure, but that these will not be expected to lead to failure unless they exceed a certain size determined by the properties of the material and the loads during its service life. The manufacturer then has the responsibility of demonstrating that he can detect, with a high confidence, those flaws exceeding this critical size. Today's inspection techniques, in general, do not provide quantitative size information. Hence when instrument sensitivities are set sufficiently high to reliably detect the required size of defect, many benign flaws also will be found. Such indications can increase cost significantly.

Therefore, the next step is to develop techniques which provide a quantitative measure of defect size. A number of ultrasonic techniques presently are being developed to make such determinations. These have, as a common feature, the collection and processing of a large amount of ultrasonic information. Included are both imaging techniques and techniques based upon inferring geometric characteristics of defects from direct measurements of the variation of the scattered ultrasonic fields with angle or frequency, or both. In each of these cases, a quantitative answer is derived from the ultrasonic data, and consequently a careful calibration is necessary so that the scattering characteristics of the defect are determined independent of the particular measurement instrument used. For the purpose of the present discussion, we will assume that the defect is to be characterized by measurements of the ultrasonic scattering cross sections, including both their absolute values and their frequency and angular dependences. An appropriate standard and calibration procedure will be outlined in the following sections.

Philosophy of Proposed Standard

In view of the widespread confusion with regards to the various terms used for standards and especially their intended or actual application, the following definitions are suggested: (*a*) the name "calibration standard" be used to refer to an ultrasonic standard solely employed to ensure that ultrasonic equipment (and operator) are functioning according to specifications, and (*b*) the name "reference standard" be used to refer to a library of scatterers of different shapes employed to aid in the identification of an unknown defect after the ultrasonic system has been calibrated.

In the context of these definitions, the calibration standard should be aimed at strictly a system checkout performance standard, which will enable the operator to know whether his system is operating up to par. This includes the electronics transmitter/receiver section and the display unit. It is not intended that the calibration standard serve as any sort of reference.

The sphere is proposed as a calibration standard. This shape has the practical advantage that orientation is not critical during fabrication. Furthermore, since exact theoretical solutions are available for the ultrasonic scattering from the sphere, it allows a direct absolute comparison of the calibration run to a theoretically based expectation curve to determine whether the apparatus is performing correctly. Moreover, the presence of verified theoretical solutions which have large variations in scattered amplitude as frequency and angle between transmitter and receiver change provides the basis for multipoint checks of the apparatus being calibrated. This can be done on a single specimen, and thus avoids some of the problems of material variability in a reference block set.

As far as calibration is concerned, the ideal material is one in which there is no attenuation and which is totally isotropic as far as wave propagation is concerned. In lieu of that, the next best step is that of a low attenuation material, still isotropic and in lieu of that, one whose attenuation is constant as a function of time. There are two principal sources to the attenuation in metal, one of which is grain boundary scattering which is expected to be stable as a function of time unless the specimen is subjected to the stress process which results in a grain growth. The other, and perhaps more important contribution to the attenuation as affects the ultrasonic calibration, is that of dislocation losses. These are well known. In this application, a material should be chosen which has a stable dislocation contribution as a function of time which in turn means that the specimen should be in a thoroughly annealed state or treated by neutron irradiation. Probably it should not be a precipitation alloy. If it is one, the dislocation structure should have had a chance to equilibrate. Stabilization of the dislocation structure also would ensure that the effects due to relaxation of residual stresses are minimized. Thus, the choice of material is not as difficult as has been indicated in the past, but should be based on readily available information with respect to the principal known causes of attenuation.

In summary, the previous sections seek to call attention to three main points: the theoretical base, the scattering concept which allows a check of the apparatus at a series of angles to be measured and compared against theoretical expectation, and finally criteria for a choice of materials.

Scattering of Elastic Waves from the Sphere

As just discussed, the goal of this study is to emphasize the "calibration standard" and develop a calibration procedure so that a typical ultrasonic system can be readied for studies to provide quantitative information about the properties of a defect. A typical defect essentially is characterized by three properties of the scattered radiation field: the angular distribution, the frequency dependence, and the absolute intensity of the scattered ultrasonic field. The calibration standard, therefore, must be able to calibrate a given ultrasonic system for these three parameters in a quantitative fashion, and it ideally should contain a very well characterized defect of a size similar to the real defects encountered in NDE. One such thoroughly characterized scatterer is the *sphere* which recently has been studied extensively on a theoretical and experimental basis, both as void [*3,4*] and inclusion [*5*] under the assumption that the scatterer is in the far-field. The spherical scatterer, therefore, is proposed as a calibration standard and the calibration procedure outlined in the next sections consists of measuring the defect properties and comparing them to the theoretical values which are now well known and invariant. The discussion will review the information on the spherical scatterer and presents some recent findings.

Theories of the scattering of acoustic waves have been developed extensively since the fundamental works of Rayleigh [*6*] and Lamb [*7,8*]. A review of the existing theories as well as some numerical results of scattered waves in elastic solids have recently been published in the monograph by Pao and Mow [*9*]. Much of the work in solids [*10,11*] was motivated primarily by the problem of calculating the attenuation of ultrasonic waves by scattering from precipitates in single crystals or from grain boundaries in polycrystalline solids.

With the application of ultrasonic techniques to the field of nondestructive testing (NDT), where ultrasonic scattering is hoped to be used to determine the shape and size of the scattering obstacle, the emphasis has shifted from the energy lost by the incident beam to the energy in the scattered beam as a function of the angle of scattering. Thus a number of workers [*12-15*] have become more interested in the differential scattering cross section (scattering per unit solid angle in a specified direction with respect to the incident beam) rather than total cross section.

Until recently, experimental investigations were limited to shapes, such as cylindrical bore holes and flat bottom holes, which readily could be machined into a solid. The successful development of the diffusion bonding technique in metals has made possible the embedding of a variety of obstacles, cavities, or inclusions, with precision controlled size and shape.

In the bonding technique, two lapped metal surfaces are brought together in high vacuum and high temperature and then bonded under uniaxial pressure with the resultant removal of all traces of the bond line. This metallurgical technique has been successfully demonstrated for titanium alloys [*15*], pure titanium and steel [*16*] and is now being used in routine production of parts. By way of example [*16*], Fig. 1 shows a cross section of a hemispherical void created by diffusion bonding together the end faces of two short cylinders, one with a smooth surface and the other with a centrally located ground-in hemisphere. A detailed look at the regions where the bond was made shows the complete disappearance of the bond line by grain growth across it. Ultrasonic measurements performed in the range from 2.5 to 15 MHz also do not reveal the presence of the bond line.

For a longitudinal wave incident on a spherical cavity embedded in a homogeneous, isotropic medium, characterized by the Lamé constrants, λ and μ, and density, ρ, the differential scattering cross-section has been shown to be [*4*]

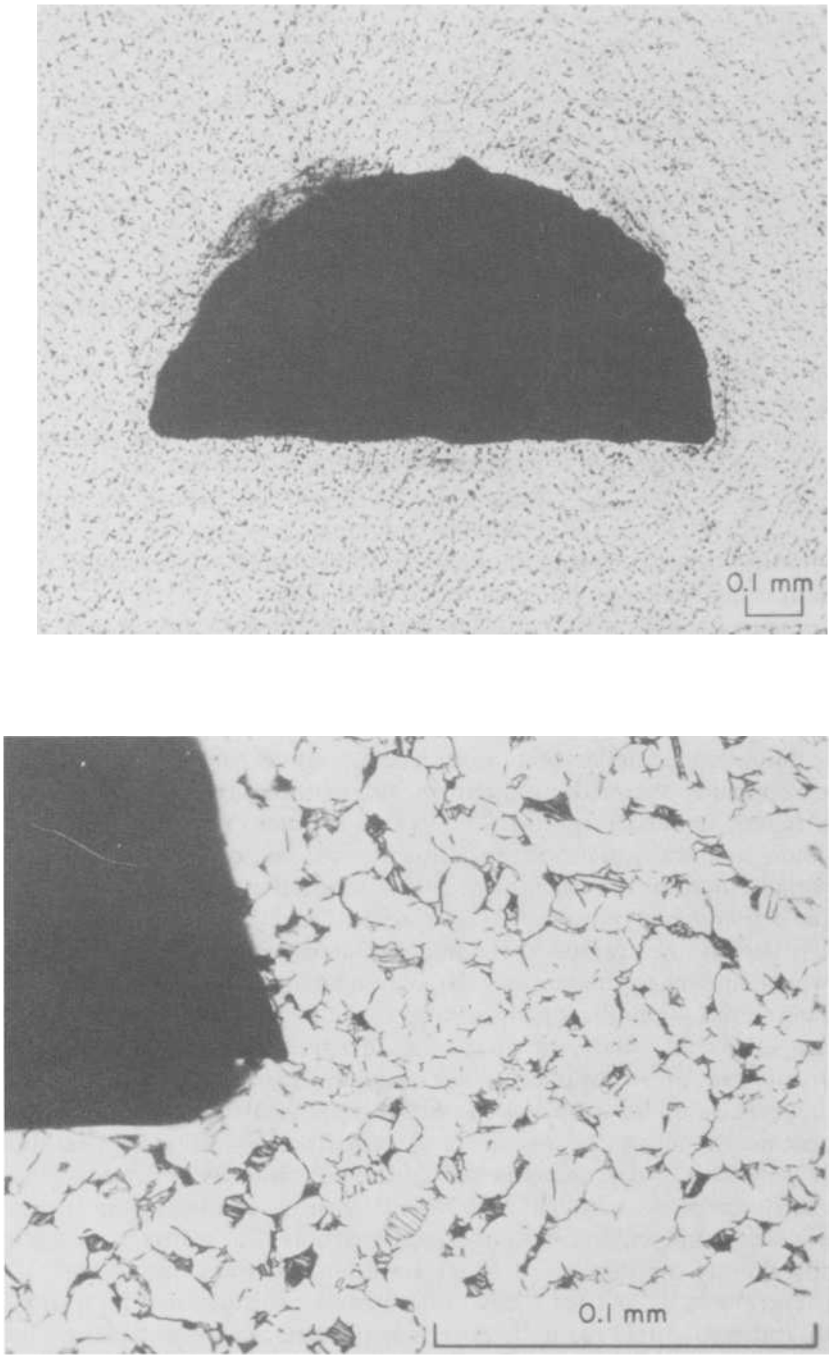

FIG. 1—*Micrographs of the cross section of a hemispherical cavity produced by diffusion bonding of two machined sections of titanium alloy. The top figure is a mosaic of several micrographs.*

$$S(\theta,\omega) = \frac{1}{k^2}\left|\sum_{n=0}(2n+1)A_nP_n(\cos\theta)\right|^2$$

$$+\frac{k}{\kappa^3}\left|\sum_{n=1}(2n+1)B_nP_n^1(\cos\theta)\right|^2$$

where

ω = frequency in radians per second,

θ = scattering angle measured from the forward scattered direction, and

$k = \omega\sqrt{\rho/(\lambda+2\mu)}$

$k = \omega\sqrt{(\rho/\mu)}$ = wave numbers of the longitudinal and mode-converted shear (transverse) waves, respectively,

$P_n^m(\cos\theta)$ = associated Legendre polynomial, and

A_n, B_n = expansion coefficients determined by matching boundary conditions.

The first term represents the scattered longitudinal wave and the second term is the scattered, mode-converted shear wave.

Figure 2 shows some representative theoretical and experimental results on the angular dependence of longitudinal waves scattered from an 800-μm diameter cavity in a titanium alloy at several different frequencies. The lines (dot-dashed, solid, and dashed) are theoretical while the dots (open squares, solid circles, and open circles) are experimental data. Good agreement is observed in spite of the use of transducers with substantially different frequency spectra. This is due in some part to taking into account in the calculations the frequency content of the ultrasonic pulse actually used in the experiments. (The figure lists the model numbers of the Panametrics transducers.) The need to take into account the characteristics of the transducer becomes primarily important in the regime where the sphere diameter is large compared to the wavelength. From these results and others [*4,5*] one can conclude that theory and experiment are sufficiently far along to give good agreement for a wide range of frequencies and transducers. The angular dependence for the range of frequencies under consideration is sufficiently different that a few measurement points in the angular range, say from $\theta = 40$ to $\theta = 60$ should be sufficient to determine the size of the spherical cavity. Conversely, the amplitude of the scattered signal is sufficiently sensitive to the frequency and scattering angle so that a well-defined spherical scatterer can be used to calibrate the response of the transducers and electronic system. Thus the presence of verified theoretical solutions which have large variations in scattered amplitude as frequency and angle change provides the basis for multipoint checks of the apparatus being calibrated. With the sphere this can be done on a single specimen, and thus avoids some of the prob-

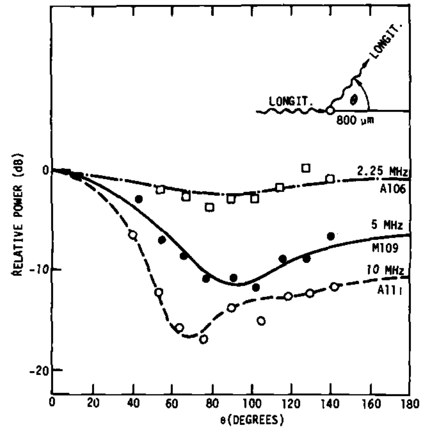

FIG. 2—*Angular dependence of ultrasonic pulses scattered from an 800-μ spherical cavity for several different frequencies. (The numbers on the right side are the model numbers of the Panametrics transducers used in the experiments.) The solid, dashed, and dash-dot-dashed lines are theoretical. The open circles, closed circles, and squares are experimental.*

lems of material variability from block to block in a set of standards. Another advantage of the sphere is that, in contrast to the flat-bottom hole, the orientation of the sphere with respect to the block surface is not critical during fabrication.

Characteristic Ultrasonic Equation

In order to develop a procedure to perform the quantitative calibration measurements just described, it is important first to consider in some detail the power transfer in a typical ultrasonic system. In simplest terms, a system can be thought of as consisting of three parts: the transmitter electronics, the ultrasonics, and the receiver electronics. The electronic components are well known and easily diagnosed with the help of conventional test equipment, for example, the linearity of the receiver may be checked by the use of a readily available precision radio frequency signal generator connected through an appropriate impedance level transformer with the transducer in series, to simulate a received voltage.

On the other hand, the ultrasonics involves several elements, namely, transduction, scattering, radiation patterns, and requires special attention in the calibration procedure. Clearly, in order to obtain detailed information about a defect in terms of the angular distribution, frequency dependence, and intensity, it is necessary to compensate for unwanted effects such as transducer response, transducer bond losses, material attenuation, beam divergence, etc., most of which change with frequency. Only if an apparatus is able to take these effects into account quantitatively will it obtain the correct signal amplitude on a standard and, therefore, be able to measure defect properties quantitatively.

Next is an analysis of what happens to the signal from the time it enters into electric terminals of the transmitter transducer to the time it leaves the electric output terminals of the receiving transducer. If the voltage pulse measured across the terminals of the transmitter transducer is given by $a_T(t)$, then its contribution at each frequency, ω, is given by

$$A_T(\omega) = \int_{-\infty}^{\infty} a_T(t)e^{-i\omega t}dt$$

Similarly for the received voltage pulse, $a_R(t)$, we have

$$A_R(\omega) = \int_{-\infty}^{\infty} a_R(t)e^{-i\omega t}dt$$

In terms of these quantities the complete description for $A_R(\omega)$ is

$$A_R(\omega) = A_T(\omega)\ \overset{\substack{\text{transmission}\\ \downarrow}}{T_T(\omega)}\ \underset{\substack{\uparrow\\ \text{propagation}}}{M(\omega)}\ \overset{\substack{\text{scattering}\\ \downarrow}}{S(\omega,a\theta)}\ \underset{\substack{\uparrow\\ \text{propagation}}}{M(\omega)}\ \overset{\substack{\text{detection}\\ \downarrow}}{T_R(\omega)} \qquad (1)$$

where

$S(\omega,a,\theta)$ = differential scattering cross section of the scatterer and is given by theory,
ω = frequency in hertz,
a = radius of the scatterer, and
θ = scattering angle measured from the forward scattering direction.

$M(\omega)$ describing the effects of the medium including travel time, attenuation, and beam divergence is given by

$$M(\omega) = (1/R\sqrt{4\pi})\ \exp - \left[i\frac{\omega}{v} + \alpha(\omega)\right]R$$

where

R = distance between transducer and scatterer, the pre-exponential takes into account beam divergence,
v = velocity of the sound wave, and
$\alpha(\omega)$ = attenuation of the medium.

$T_T(\omega)$ may be viewed as the transfer function for the transmitter transducer in that it takes into account the conversion efficiency of the transducer, losses in the transducer and in the bond between the transducer and the specimen, the characteristics of the radiation pattern, and the effect of the acoustic impedance of the specimen on the output of the transducer. This is a very complex function, and its analysis is made even more difficult by the empirical fact that it changes with time because of the well-known aging of piezoelectric ceramics. It is clear that knowledge of $T_T(\omega)$ is essential for a quantitative measurement, but it is equally clear that $T_T(\omega)$ cannot be prespecified by the transducer manufacturer. It, therefore, is proposed that $T_T(\omega)$ be evaluated prior to each series of measurements as part of the calibration procedure, and one technique for doing so will be outlined next. $T_R(\omega)$ is the transfer function for the receiving transducer and involves similar considerations with additional features as the question of reciprocity and the effect of the physical aperture which determines how much of the scattered radiation is intercepted and converted.

The characterization of transducers as to their radiation pattern, conversion efficiency, and bandwidth, in principle, may be determined if the transducer's construction and constituent parts independently are known [*17–19*], but most often the internal details of the transducers are unknown and subject to statistical variations and aging. Alternatively, it is possible to determine the radiation field at any point within or beyond the Fresnel zone based upon measurements within the zone by implementing inverse scattering analysis. In fact, this has been demonstrated successfully recently [*20*] with the aid of a network analyzer to measure the phase and amplitude of the radiation pattern and an on-line minicomputer to store and process the data. To complete the transducer characterization, it is necessary to determine the electrical to acoustical transduction efficiency as well, and there are numerous procedures to do this involving calibrated sources, acousto-optic interactions, or reflections from known reference surfaces [*20*]. Thus the wave amplitude anywhere in the radiation pattern can be related directly to the input electric signal.

At this point, an important simplification is made, motivated by the realization that the side lobe structure of the transducer radiation pattern plays little or no role because it involves a low signal-to-noise ratio, a rapid change of amplitude with angle, and mode conversion at the face of the transducer. Therefore, it is postulated that, whatever the use of the transducer, the main beam (whether wide or narrow) plays the major role and that the peak of the main beam be oriented ideally into the direction of the normal to the transducer face, that is, that any deviation of the main beam from the transducer normal be viewed as a deficiency to be uncovered in the typical calibration procedure. With this simplification it is possible to introduce the concept of the "effective gain" of a transducer.

The effective gain, $G(\omega)$, of a transmitting transducer is the power per unit solid angle in the forward direction in terms of power delivered to the transducer terminals. For a receiver transducer $G(\omega)$ is the maximum power delivered to a load matched to the transducer transmission line of assumed zero loss when the power per unit solid angle incident of the transducer is known.

This definition effectively lumps into one parameter all the processes and losses involved in taking the electrical energy from the input terminals into the acoustic energy of the main beam as it propagates in the medium normal to the transducer face. $G(\omega)$ is analogous to the gain of an antenna in radar and becomes a figure of merit. $G(\omega)$ is unitless since it is a ratio and may best be expressed in decibels. For the sake of brevity, the discussion now disregards the phase factors implicitly accompanying the terms in Eq 1. Although this simplifies the treatment, it generally is not necessary and in fact undesirable since the phase carries valuable information. The more general treatment, including phase factors, is given elsewhere [*21*].

The "receiving pattern" of a transducer is defined analogous to its transmitting pattern and as a consequence of the reciprocity theorem [*22,23*] these patterns are identical for most types of passive linear electroacoustic transducers.

For a receiving transducer it has also been shown[3] in analogy to antenna theory [*24*] that for the receiver the ratio of the transfer function, T_R, to the effective gain, $G_R(\omega)$, is a constant

$$\frac{|T_R(\omega)|^2}{G_R} = \frac{\lambda^2}{4\pi}$$

In terms of these newly defined quantities, the *characteristic equation* for the ultrasonic system becomes

$$\frac{|A_R(\omega)|}{|A_T(\omega)|} = \frac{a\lambda}{R^2(4\pi)^{3/2}}|S(\omega,a,\theta)|\sqrt{G_T(\omega)G_R(\omega)}\exp\left[-2R\alpha(\omega)\right] \quad (2)$$

All quantities in this expression can be specified by theory and experiment so that the problem can be solved on a quantitative basis. For simplicity, Eq 2 does not take into account mode conversion explicitly. This consideration, however, is covered fully by the more general treatment [*21*].

[3] Richardson, J. M., private communication.

Calibration Procedure

Measurement of G(ω)

The determination of $G(\omega)$ for a particular transducer now becomes a straightforward problem. Equation 2 is adapted for the case of a single transducer used as transmitter and receiver. On the strength of the reciprocity theorem one may write

$$G(\omega) = \frac{(4\pi)^{3/2}}{a\lambda R^{-2}} \frac{|A_R(\omega)|}{|A_T(\omega)|} \frac{\exp\left[-2\alpha(\omega)R\right]}{S(\omega,a,\theta)} \tag{3}$$

The experimental procedure amounts to letting a transducer direct its on-axis radiation onto a target of known scattering cross section $S(\omega,a,\theta)$ embedded in a medium of known or measured attenuation $\alpha(\omega)$ and measuring the ratio of output-to-input signal voltage at the desired frequency ω. If the intended use of the transducer is in a water bath, then the target could be a metal ball suspended by a string. If the intended use is in a metal, then the target could be a spherical cavity or inclusion embedded in the metal by, for example, diffusion bonding techniques. If the transducer is shock excited so that it emits a range of frequencies as in broad band application, it becomes necessary to spectrum analyze the input and output signals and form the ratio for each frequency separately. It is clear that any deficiency in the transducer, such as "hot spots," split main beam, tilted main beam, or poor signal-to-noise ratio, will show up as a decrease in the value of $G(\omega)$ so that it is indeed a figure of merit that can be used effectively in the characterization of the transducer. More importantly its value must be known for use in Eq 2 so that a quantitative calibration can be accomplished.

Once the G-factor of one transducer is established over the frequency range of interest, this transducer can be used as a standard to determine the G-factor of another transducer. The principle for doing this has been discussed in the literature [*25*] in great detail, and here only the procedure will be summarized. The transducer to be calibrated is first set up with a scattering center as just described or another transducer as transmitter. The received voltage $A_\mu(\omega)$ is noted; then the transducer is replaced by the standard transducer for which $A_s(\omega)$ is measured with the use of the same detection apparatus. The G-factor of the transducer is then

$$G(\omega) = \frac{|A_\mu(\omega)|^2}{|A_s(\omega)|^2} \times \text{gain of standard}$$

Calibration of Entire System

With the determination of $G(\omega)$ for two transducers, all the parameters are specified for using the ultrasonic system in, say, "pitch-catch," to measure quantitatively $S(\omega, a, \theta)$ and compare it to its theoretical value for the specific scatterer making up the calibration standard.

In terms of the characteristic equation

$$S(\omega, a, \theta) = \frac{(4\pi)^{3/2}\,|A_R(\omega)|}{a\lambda R^{-2}\,|A_T(\omega)|}\frac{[\exp - 2\alpha(\omega)R]}{\sqrt{G_T(\omega)G_R(\omega)}} \tag{4}$$

where

$$|A_R(\omega)| = \beta|V_R(\omega)|,\ V_T(\omega) = \int_{-\infty}^{\infty} V_R(t)e^{-i\omega t}dt$$

$|V_R(t)|$ is the echo displayed on the oscilloscope after being amplified by an amount, β, in a wide-band receiver (if the receiver is a tuned receiver, its frequency dependence $\beta(\omega)$ has to be taken into account).

Specifically, a goniometer could be constructed to handle two transducers and a centrally located sphere. The three parameters, that is, intensity, frequency dependence, and angular dependence, then would be measured and compared to theoretical predictions. If disagreement is found, the system can be analyzed step by step with the aid of test equipment for the electronic components and with the aid of the characteristic equation for the ultrasonic system.

Figure 3 shows a photograph of a measurement fixture which has been used effectively in the measurement of data such as shown in Fig. 2, and this fixture would be suited ideally for the calibration procedure. Shaped in the form of a cylinder with polygonal cross-section, the titanium alloy specimen makes contact with two commercial transducers, one fixed as transmitter, the other one capable of moving from one specimen face to the next in angular increments easily measured on the calibrated dial. The specimen contains an 800-μm-diameter tungsten-carbide inclusion which is equidistant from all the faces. With this fixture, it is possible to obtain the G-factor for each of the transducers used and then to calibrate the system in the manner, outlined.

Summary

In this report the subject of ultrasonic standards is reappraised in terms of history and future needs. Current changes in the philosophy for design and inspection establish the trend towards the need for providing quanti-

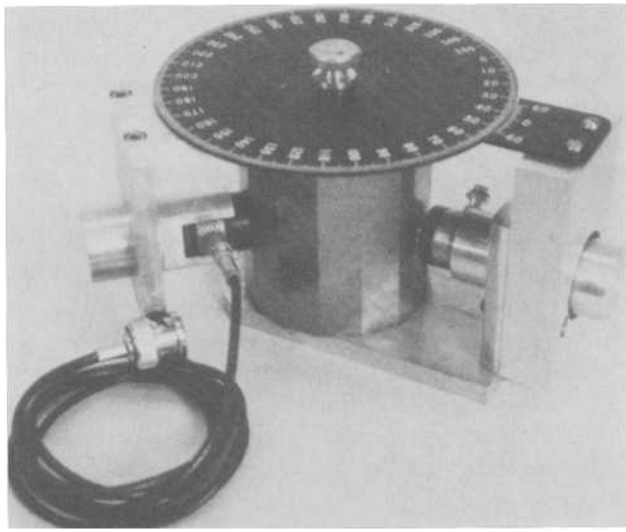

FIG. 3—*Photograph of measurement fixture including a polygon specimen and pair of commercial transducers.*

tative size information. Fracture mechanics design procedures are being adopted which recognize that defects are present in any substructure, but these will not be expected to lead to failure, unless they exceed a certain size determined by the properties of the material and the loads during its service life. Consequently the manufacturer now has the responsibility of demonstrating that he can detect, with a high confidence, those flaws exceeding this critical size. Whatever the method of size determination (whether imaging techniques or direct scattering measurements), a quantitative answer is derived from ultrasonic data and consequently a careful calibration of the ultrasonic apparatus is mandatory. Today's inspection techniques, in general, do not provide quantitative size information, in part because of a lack of adequate calibration standards and procedures. This report describes how an ultrasonic system might be checked out to provide quantitative NDE data by using a new standard and calibration procedure.

The backbone of the procedure is an ultrasonic characteristic equation which relates the transmitter signal to the received signal in a quantitative way. With the help of this equation, the scattering parameters, that is, the angular dependence, frequency dependence, and amplitude of the differential scattering cross section, may be determined from data obtained on a calibration standard. The results may be compared then with the invariant theoretical solution to verify the proper operation of the ultrasonic system. A key feature of the development is the *G*-factor which is a proposed figure of merit for a transducer. The calibration procedure may be summarized as follows.

Step 1: Select a calibration standard on the basis of the calibration frequency chosen and a set of reference tables giving the appropriate standard for that frequency and the theoretical values for $S(\omega,a,\theta)$.

Step 2: The attenuation and velocity for the selected standard is obtained from the specification and data sheets accompanying the standard. (These data also could be checked in measurements using established techniques.)

Step 3: Each of the transducers to be used is calibrated over the frequency range of interest. This ideally would be accomplished with recently made available techniques for relating the complex acoustic radiation field to the electric input signal for the material of interest. Alternatively, a figure of merit, the G-factor, would be determined in a *pulse echo experiment* on the calibration standard of Step 2. This determination implies a knowledge of the attenuation and its frequency dependence for the calibration standard.

Step 4: Now all the parameters are specified for using the ultrasonic system in *pitch-catch* on a calibration standard to quantitatively measure the electrical output signal for several different angles and frequencies, and used to calculate the differential scattering cross section $S(\omega, a, \theta)$.

Step 5: The measured $S(\omega,a,\theta)$ is compared quantitatively with the theoretical $S(\omega,a,\theta)$ value for the specific scatterer making up the calibration standard. If the ultrasonic system is calibrated, the two sets of values for $S(\omega,a,\theta)$ will be identical for all the angles and frequencies considered. If the values do not agree, the system is not calibrated and some of the previous steps should be repeated. The characteristic equation developed for the system should provide valuable clues for the source of discrepancy. (A check of the electronic components with the help of conventional test equipment might be desirable.)

The calibration standard proposed is the far-field sphere (cavity or inclusion embedded in a solid or a ball suspended in a liquid). As a result of recent work, the sphere now is understood well theoretically and experimentally and can be reproducibly fabricated in a solid by diffusion bonding techniques. Major advantages of the sphere are that it can be reproducible fabricated by bonding, it has no preferential orientation, the transducer alignment is not critical, it allows multipoint checks on a single standard block, and it gives a sufficient dynamic range to make linearity checks meaningful.

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Automated Nondestructive Evaluation Systems and Standards

REFERENCE: Schmitt, J. K., "**Automated Nondestructive Evaluation Systems and Standards,**" *Nondestructive Testing Standards—A Review, ASTM STP 624,* Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 312–316.

ABSTRACT: This paper presents the cases for automating a nondestructive evaluation (NDE) operation. Cautions are presented on the use of automation as are a series of steps and a checklist for the design and procurement of a system. Reference specimen use, cautions, and replacement recommendations are included.

KEY WORDS: nondestructive tests, standards, automation, specimen damage potential

It is all too common to feel that if an nondestructive evaluation (NDE) operation works well, if it only could be automated, it would work better. Some operations, at this time, defy automating and likely will for the foreseeable future. Other NDE operations are readily automatable. Then it becomes incumbent on the user to make all the necessary decisions to choose how automated a system should become. Varying degrees of automation, up to 100 percent, can and are being utilized.

Why Automate a Test

There are generally five reasons to automate an NDE operation.

1. The operation is too difficult to do manually. By this it is meant that the motions (translation, rotation, reproducibility, etc.) require abilities not possessed commonly or not trained readily.

2. The operation is too time consuming to do manually. At this point it is presumed that the motions can be done manually, but the examination is so tedious that it requires inordinate amounts of time to perform. One example would be the manual recording of ultrasonic thickness measurements on steel tanks where hundreds of identical vessels are involved.

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3. The operation is too expensive to do manually. If both the motions and time are available, but the costs of performing the operation are excessive, automated NDE may be the better way. For example, if shutting down a manufacturing line is necessitated by the required NDE, speed (coupled with accuracy and reliability) of that NDE operation will be of the essence.

4. The volumes required are too great to do manually. In the automobile industry there is a saying "cheaper yet by the millions." This can and does create problems. For example, at one automobile corporation two parts per car translates to 1000 quality approved parts each and every hour whether breakdowns occur or not! The volume consideration alone can well dictate highly automated or unstaffed NDE systems. The alternative would be more floor space utilized, more equipment inefficiently applied, and more people who need training, etc. Overall this is a much less efficient alternative.

5. The operation may be too dangerous to do manually. In addition to the obvious examples of nuclear industry operations, certain grades of drawn steel wire are required to be inspected for surface flaws. These operations are automated for two reasons. The speed (several hundred feet per minute) is great, but more significantly, if at that speed the wire broke, operator safety could be jeopardized.

Evaluate the Potential Success of Automating

Early on, one should take a step back and look at the overall problem and the subject of automating to attempt to determine, on a preliminary basis, the potential for success. Ask the following questions.

1. Why are we doing this? Or what is the fundamental requirement and where does it come from?

2. What are the economic and political aspects of the problem?

In many instances, the answers to these questions are very revealing. At this point, it should be possible to make a logical comparison of what is desired to be accomplished with NDE as opposed to what is expected to be accomplished. This logical comparison defines the element of risk involved in NDE and in systematizing the operation. Necessary time must be taken to make carefully a list of all factors known at that time. List everything no matter how meaningless it may seem to be.

Take into consideration all the factors which have been listed and define in as simple a statement as possible the objective of installing the NDE system.

Three examples which might serve to point out differences in philosophy are as follows.

1. The objective of installing this system is to comply with the existing

American Society of Mechanical Engineers (ASME) code requirements for the product.

2. The objective of installing this system is to detect and segregate that portion of the product which is not in accord with the metallurgical requirements for this application.

3. The objective of installing this system is to satisfy the group quality control auditor.

Not surprisingly, systems have been installed for each of these requirements. From a technological standpoint, Example 2 is by far best with Example 1 a close second.

Selection of NDE Method

In many cases the NDE method to be systematized is quite clear from the beginning of the program. There are a few instances in which there are two or more NDE methodologies which hold promise. In cases such as this, all promising NDE methodologies must be evaluated with equal objectivity and vigor. At this point in the program consideration should be given to the capability of the method alone, not to how the method could be systematized.

One sure route to failure is to systematize an NDE operation which is incapable of achieving the objectives set forth earlier. Determine the capabilities (both positive and negative) of the NDE methodology first. On occasion this step ends the development, as the desired evaluation cannot be done.

Where at least one NDE method can do the job required, consideration must then be given to the following questions.

1. How can this NDE method be used in the system?
2. What system characteristics exist that would impede the use of NDE?
3. What system constraints exist that would impede the use of NDE?

Once these questions have been resolved satisfactorily, the system application study must be conducted.

System Application

Up to now concern has been centered about, "can the technique which appears to work be systematized." Prior to any later steps, the question of, "will it actually work on our product," must be settled. If at all possible, secure actual products as specimens for the experimentation. Occasionally, as in the case of new products, this is not always possible. It is almost always possible to secure a product of similar characteristics. Carefully choose the specimens to represent all known conditions plus anything foreseeable as "possible." Construct an experiment that will give a list of accomplishments and limitations with the current state of NDE. In using different equipment, it is likely that differences in capability will surface. It is unlikely that any piece of equipment operated in any fashion will yield perfect correlation. A judgment will have to be made relative to the "can do" and "can't do" of the proposed system.

Specifying the System

To adequately specify an NDE system, three items must be clearly defined: (*a*) the requirements of the test, (*b*) the requirements of the system, and (*c*) the requirements of performance.

In so doing, as a minimum include: through pass rate, NDE statistics, space, infeed, outfeed for good, outfeed for rejects, services, floor test, warranty, installation start-up, concept drawings, ruggedness required, block diagrams, interfaces, specimens, plant specifications, delivery requirement, penalty clauses, documentation, plant environment, education of personnel, and compliance statement.

At this point, the criteria for the acceptance judgment should be established clearly. Whatever criteria is established, all system proposals must be judged alike.

Standards for NDE Systems

Standard specimens for the system must be available for use by authorized personnel once the system has been installed in the using facility.

Table 1 lists, in general terms, the potential for standard damage for various system types and cautions in their use. Notwithstanding, an evaluation of the interaction of the system with a specimen run numerous times (several hundred times at least) must be conducted. This will indicate if any specimen interaction deterioration occurs. In most systems the amount of this deterioration is insignificant. For those systems, three sets of standard specimens are sufficient. Data on the system interaction with each part of each set must be recorded and the data held in a secure location, along with the two sets of standard specimens which are not used initially with the system.

In the event that standard specimen deterioration occurs, it is necessary to have numerous sets with appropriate data secured as mentioned before. Extreme care must be exercised so that any standard specimen is not used beyond its useful life. It must be noted that standard specimens need not cause the system to go-no-go at their interactive values. They need only permit the user to establish or maintain the specified operational characteristics.

Once the unit has been operating for a time, new standard or reference

TABLE 1—*System-specimen damage potentials.*

Type of NDE System	Potential for Standard Damage	Remarks
Eddy current for metallurgical properties (comparator)	very slight	System usually is noncontacting. Transport mechanism is only source of potential damage. With high coil current part may heat up changing its response.
Eddy current for surface flaws (crack detector)	slight to moderate	System can be contacting or noncontacting. Surface riding probe with wear shoes can lead to standard damage. Rotary transformer type reduces damage potential to transport mechanism only.
Ultrasonic	slight to moderate	Immersion system liquids can corrode standards—mechanical damage potential is very slight. Contact system liquids as above —potential for mechanical damage is increased.
Magnetic particle	moderate to severe	Particles must be removed thoroughly and area kept clean—mechanical damage potential quite slight. Part should be demagnetized after each use.
Penetrant	moderate to severe	Penetrant must be removed thoroughly and area kept clean—mechanical damage potential quite slight. Some metals are reactive to halogens. Care should be exercised in its selection.
Radiographic	slight to moderate	Similar to eddy current (comparator) except that radiation is involved.
Other	slight to severe	Depends on many factors.

specimens likely will be desired. From the outfeed, during a run of parts several can be selected that careful examination reveals to be just barely good or bad. As time goes on these specimens can be used to refine the process and even change the limits of the NDE operation.

Conclusions

Undoubtedly we will see more automated NDE systems in the future. Standards for these systems do not present any special problems other than the increased possibility for physical damage. Reasonable care and attention can minimize these problems.

Harold Berger[1]

The National Bureau of Standards Program in Nondestructive Evaluation

REFERENCE: Berger, Harold, "**The National Bureau of Standards Program in Nondestructive Evaluation,**" *Nondestructive Testing Standards—A Review, ASTM STP 624*, Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 317-327.

ABSTRACT: The rationale and present technical content for the National Bureau of Standards (NBS) program in nondestructive evaluation (NDE) is presented. Needs for improved NDE measurement reliability and accuracy, needs that led to the establishment of this new program, are discussed. The present technical program is described. It includes work related to acoustic-ultrasonic, radiography, visual, electrical eddy current, microwave, penetrant and thermal testing, and wear debris analysis. The program content is summarized in two tables. Outputs from this program are indicated; these include standards and methods of measurement, calibration services, and standard reference materials.

KEY WORDS: nondestructive tests, standards, acoustics, calibration, electrical measurements, eddy currents, microwaves, standard reference materials, thermal cycling tests, ultrasonics, visual testing, wear tests

Although you probably do not think about it consciously, many of the measurements involved in our lives, at home and at work, are traceable to the National Bureau of Standards (NBS). The NBS works with state and local agencies to be sure that a pound of tomatoes in California gives the customer the same mass as one pound of tomatoes in any other state. Similarly, units of volume, length, force, and many others are traceable to NBS measurements and calibrations. That is one of the prime missions of NBS.

The basic mission of NBS derives from the Organic Act authorization in 1901. Under the act, the Secretary of Commerce was authorized to undertake the following functions:

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"...development of national standards"
"...determination of physical constants and properties of materials"
"...development of methods of testing materials"
"...cooperation with other governmental agencies and with private organizations in the establishment of standard practices"
"...advisory service to government agencies"
"...serve special needs of the government"

The first three of these functions and their relationship to nondestructive evaluation (NDE) are discussed in this report. However, the NBS/NDE program embraces all these functions.

The NBS has a long history of providing measurement and standards assistance to industry. Although a formal program in NDE is relatively new at NBS, associated measurements in fields such as X-radiation and electrical conductivity have been available for some time. The present program in NDE is beginning to address the measurement and standards needs of the six major industrial NDE methods, visual optical, penetrant, magnetic particle, eddy current, X-radiographic, and ultrasonic. In addition, there is substantial interest in new NDE methods such as acoustic emission, neutron radiography, wear debris analysis, and microwave testing. These technical programs are described in a later section of this paper.

The needs and opportunities in NDE measurements and methods have been described in previous publications [*1,2*].[2] In summary, these reports show that the demands on NDE are changing and that the present NDE measurement methods must become more reliable by becoming more quantitative and reproducible. The changing demands come from such things as increasing emphasis on standards related to performance criteria [*3*], needs for quantitative results for fracture mechanics design [*1*], and economic factors from liability judgements [*2,4*] and product recalls [*2,5*]. As far as NDE measurements are concerned, there is strong evidence that reliability needs to be improved [*2,6,7*].

NDE Program Plans

In order to improve NDE measurements and, thereby, to improve the reliability and durability of materials, a program in NDE was established at NBS in 1975. The plans for this program are summarized as follows.

Near to Medium Range (1 to 5 Years)

The NDE program is emphasizing the needs for improved measurement and calibration standards and procedures for the six commonly used

[2] The italic numbers in brackets refer to the list of references appended to this paper.

industrial methods (visual optical, magnetic particle, ultrasonic, penetrant, radiographic, and eddy current). This emphasis will help bring these methods to a point where measurements can be made in a more meaningful and reliable manner. Reproducibility of measurements will be improved; calibrations will have better traceability.

Although the emphasis is as indicated during this period, work to understand materials performance better and to develop other NDE methods will also be initiated.

Long Range (beyond 5 Years)

Once the NDE program has addressed the basic measurement problems of the six major methods, there will be two significant remaining tasks. The major one is to relate material behavior to NDE indicators so that the performance of materials under both new and in-service conditions may be predicted reliably. To do this, the NDE technology must be capable of quantitative and reliable flaw detection. In addition, the nondestructive measurement of material properties such as hardness or residual stress also will have to be accomplished. Therefore, a second major task is the development of additional NDE methods for material property measurements.

The successful accomplishment of these tasks will fill future needs now becoming apparent. The NDE profession must develop methods that are more reliable and accurate in relating flaw and material property measurements to the performance of materials and components. Above all, this requires a shift from qualitative to quantitative measurements combined with the analytical tools to make accurate failure prediction estimates. The improved measurement and reliability capacity accomplished early in this program will contribute to that need, as will the development of methods for the determination of material properties. In the long term, these program objectives will lead to significant savings by helping to make realistic material and performance specifications a reality. In addition, of course, there will be appreciable impact related to productivity, conservation, and safety.

Present Technical Program in NDE

The present technical program at NBS involves several NDE methodologies. The strongest components are concerned with acoustic-ultrasonic and radiographic investigations. However, work is in progress in many additional areas. Each of these is summarized next and in Tables 1 and 2. Table 1 includes the traditional test methods, and Table 2 presents the newer, developing methods. The programs discussed include both NBS and other agency-sponsored work.

TABLE 1—*Methods commonly used in industry for NDE.*

Method	NBS Program
Ultrasonic	development of test methods; transducer calibration; test blocks; instrumentation development; instrumentation characterization; applications
X-ray radiography	measurement of unsharpness; characterization of scattered radiation; improved screens and grids; development of scatter inspection methods; applications
Visual	characterization of visual test parameters; improved test for visual acuity under actual test conditions
Eddy current	development of methods for ac-dc conductivity measurements; standards for eddy-current measurements
Penetrant	preparation of improved crack plate standards for penetrant sensitivity test

TABLE 2—*Newer methods for NDE.*

Method	NBS Program
Acoustic emission	theory of spectral characteristics from moving defect; transducers; instrumentation; applications
Neutron radiography	characterization of neutron beams; development of improved detectors; preparation of recommended practice; development of three dimensional methods; applications
Microwave	development of methods for measurement of moisture in building materials; application to concrete, relate to cure and strength
Wear debris	characterization of particle size and distribution; engine condition monitoring; improved analytical methods for small particles
Thermal	improved microcalorimeter for test of battery life

Acoustic-Ultrasonic Programs

Work is in progress to develop methods for calibration of ultrasonic [*8*] and acoustic emission [*9*] transducers. Spectral characteristics, beam profile, and total sound power measurements are being addressed. A transducer calibration service is available (see Ref *8* for method description); plans include an expanded service.

Ultrasonic test blocks [*10*] are under study in a program partially funded by the U.S. Air Force, U.S. Army, and the National Aeronautics and Space Administration (NASA) to determine the reasons for variability of these metal calibration blocks and to find ways to reduce that measurement variability. Further directions for this effort include the development of material-independent test blocks and the development of well-characterized fatigue cracks that could serve as a calibration for many NDE tests. In the near term, sets of calibrated aluminum test blocks will be available on a loan basis.

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

Application [*11,12*] of these NDE methods is being made to metals, ceramics, polymers, building materials, and electronic components. Specific application studies involving advanced ultrasonic instrumentation also are being conducted for the U.S. Nuclear Regulatory Commission (for steel reactor components) and the National Institute of Health (ultrasonic diagnostic equipment for cancer detection).

A program to develop a theoretical basis for acoustic emission spectral analysis to characterize moving cracks or defects recently has started [*13*], partially funded by the Electric Power Research Institute. This program includes work for improved transducer calibration. In this program, the theory to predict the acoustic emission spectral characteristics expected to be emitted by a moving defect will be developed and verified by experimental work in both transparent materials and metals [*13*]. This work also includes close participation with standards and code development groups, particularly the American Society for Testing and Materials (ASTM) and the American Society of Mechanical Engineers (ASME).

Radiography

Current programs involve work in both neutron and X-radiography. The X-ray program includes investigations of standards for the measurement of spatial resolution in radiographic systems (with initial emphasis on methods for determining radiographic unsharpness) and for the characterization of real-time fluoroscopic systems. Developments in progress include work on improved X-ray screens and grids, determination of scattered radiation content and its effect on radiographic detectors, and a scattered radiation approach to X-ray inspection that would permit such inspections to be accomplished from one side [*14*].

The neutron radiographic studies are made primarily with a thermal neutron radiographic facility at the NBS Research Reactor. Work has been done with a 3-MeV accelerator and a 100-MeV linear accelerator; a californium-252 source is also available. A recommended practice for thermal neutron radiography is being developed in collaboration with ASTM Subcommittee E7.05 on Neutron Radiography. Standards for characterizing neutron beams for radiography and gaging are under investigation. Characterization will include neutron intensity and energy, gamma intensity and energy, beam size and uniformity, and angular divergence. Development work has concentrated on neutron image detection [15]; studies include real-time systems, alignment methods using convenient detectors such as Polaroid film and radiographic paper, improved neutron conversion screens, and gas-cell detectors.

Application feasibility studies and special technique developments also are undertaken. An example of the latter is work to demonstrate three-dimensional thermal neutron radiography in collaboration with Argonne National Laboratory.

Electromagnetic Methods

Visual—A program recently initiated will examine methods for the measurement of visual acuity under typical NDE inspection conditions. This will include consideration of subdued lighting common in radiographic reading rooms and the dark booth situations typically used in fluorescent penetrant and magnetic particle inspection.

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

Electrical, Eddy Current—Facilities for direct-current electrical conductivity measurements are essentially complete as the first stage of a new program in electrical and eddy-current methods. An alternating current conductivity measurement facility is planned also. Future directions for this work include the establishment of measurement procedures for conductivity standards over the range 1 to 100 percent International Annealled Copper Standard (IACS) and methods for the calibration of eddy-current test equipment.

Microwave Methods—Microwave measurements are being used to determine physical properties of materials. A new part of the NDE program utilizes microwaves to measure moisture content of concrete. These measurements will be related to the strength of the material. This represents one area in which NDE methods are being explored for applications in the building industry. Future work to measure moisture content of other building materials is planned.

Penetrant Testing

An investigation of the feasibility of preparing a master crack calibration plate for the evalution of penetrant sensitivity is beginning. It is proposed to electrodeposit a heavy, nonadherent layer of nickel over a suitable crack plate and to use the removed nickel master to prepare duplicate calibration plates.

It is known that this method will reproduce accurately crack dimensions as small as 3 μm wide by 3 μm deep. Methods for reproducing smaller dimensions are under study.

If the method proves useful, then the nickel master plate could be characterized very well. The calibration plates produced from it could be relatively inexpensive and could be discarded after some period of use. This would minimize problems presently encountered concerning the uncertainty of crack size due to crack growth or cleaning difficulties.

Wear Debris Analysis

Detection of worn metal in lubricants in mechanical machinery is used now in both military and civilian programs to determine the proper time for engine, bearing, and transmission overhaul. This method now is being expanded in a current NBS program (partially funded by the U.S. Navy) in which the wear debris particles in the lubricant are detected, sized, and examined in order to determine where and by what mechanism wear is occurring [*16*]. Magnetic methods for obtaining size distributions of wear particles are used. X-ray microanalysis techniques have been developed for particles in the micrometre range. The techniques offer increased sensitivity for engine condition monitoring compared to conventional oil analysis methods.

Thermal

A newly initiated program proposes to develop a method for the NDE of batteries used in critical assemblies such as cardiac pacemakers. A microcalorimeter capable of measurements in the 0.2 to 1000-μW range will be used to measure heat generated in batteries and, in some cases, pacemakers, under a variety of conditions. Heat generation by new and partially discharged batteries will be measured under no-load conditions as a measure of self-discharge. A high rate of self-discharge would indicate short shelf life and may indicate short duty life. Heat generation will also be measured under load conditions. It is anticipated that the work will be done in combination with other nondestructive methods to determine power cell quality.

Some Recent Technical Accomplishments

Although the NDE program is new at NBS, it draws on related work that has been under way for some time. That being the case, there are several areas in which significant progress has been made. Some examples include the following.

Calibration Procedures for Acoustic Emission Transducers

In order to understand the meaning of acoustic emission signals, it is necessary to determine the intensity, timing, and spectrum of the emissions. To accomplish that, one must know the spectral response of the transducer used for detection. A new method for calibrating acoustic emission transducers has been proposed by NBS [*9*]. The method is based on a comparison of the actual response of the transducer to the theoretical response from a step function of stress. The theoretical response has been confirmed experimentally using a breaking glass capillary tube as the emission source. Work is now in progress to replace the aluminum transmission block used in proving the method with a large steel block that will be more representative of a typical reactor measurement problem. The steel block tests will serve to assist ASME code committees in deciding on a recommended method for transducer calibration. A limited acoustic emission transducer calibration service is planned.

Ultrasonic Reference Block Measurements

Cylindrical metal blocks containing flat bottom holes are used to calibrate ultrasonic test equipment. There has been appreciable variability in these blocks and the resulting calibrations. An NBS program, partially sponsored by the U.S. Air Force, U.S. Army, and NASA, has been under way to determine the primary causes of this variability [*10*]. A representative data base for aluminum test blocks has been established. Metallurgical variations, some remaining from ingot solidifications, have been shown to account for the major part of the observed variability, some of which has been shown to be as great as 800 percent. Replicate blocks from one batch of aluminum have been fabricated at NBS and show variations in ultrasonic response of less than 10 percent through a frequency of 15 MHz. This compares with an average variation of $\backsim$ 30 percent for field blocks. Plans are to establish a loan service for calibrated reference blocks.

Pulse Compression Methods for Ultrasonic Inspection

One of the present problems in ultrasonic inspection is the difficulty of putting sufficient pulsed ultrasonic power into an attenuating specimen (such as a stainless steel reactor component) to be able to detect a reflection signal from an internal discontinuity. One method for accomplishing this is to spread the ultrasonic pulse over a longer time so more power may be put into it. If the received pulses then can be compressed in time so that they retain the high signal level and, in addition are capable of resolving closely spaced discontinuities, then a significant improvement in ultrasonic testing will have been realized. This pulse compression technique, which is used extensively in chirp radar systems, has now been applied successfully at NBS to ultrasound NDE.[3] A compression factor of 7:1 has been achieved and work is in progress to extend it to 20:1. Ultimately, pulse compression ratios exceeding 100 should be achievable.

Three-Dimensional Thermal Neutron Radiography

It is difficult to separate depth information from radiographic inspection results; complex objects are difficult to inspect by radiography because of the many overlaying shadows. The separation of radiographic images from individual object planes can overcome these problems. Methods for performing this three-dimensional radiography with thermal neutrons have been demonstrated recently [*17*]. A multiple-film laminagraphy method, utilizing as many as nine individual thermal neutron radiographs taken over a 40-deg angular coverage, has been shown to provide a spatial resolution of 0.25 mm for an object thickness of 6 cm. Tests were made on several test objects and on a simulated fast reactor fuel subassembly to demonstrate applicability.

Discussion and Conclusions

The accomplishments indicated give some idea of the type of outputs the NDE community may expect from NBS. These examples included calibration services both by in-house measurements and loaned calibration services, and improved methodology. In addition, there are plans to expand the range of standard reference materials (SRMs) related to NDE. In the words used in the NBS Catalog of Standard Reference Materials [*18*], "SRMs are used to calibrate measurement systems and to provide a central basis for uniformity and accuracy of measurement." They are used widely for a broad range of industrial measurements; several of them are used for NDE measurements. These include an X-ray film step tablet (Ref *18,* SRM 1001, p. 65) used to calibrate densitometers, coating thickness standards (Ref *18,* pp. 45–48) used to calibrate beta backscatter, X-ray and eddy-current measurements of coating thickness, and metallo-organic compounds (Ref *18,* p. 36) used to determine concentrations of metal in lubricating oil for wear analysis. The role of SRMs in achieving measurement compatibility is discussed in the recent review by Cali and Stanley [*19*].

Some additional future outputs that are expected from the NBS/NDE program include recommended practices for thermal neutron radi-

[3] Linzer, M., National Bureau of Standards, unpublished work.

ography, the measurement of radiographic unsharpness, and the measurement of visual acuity. In addition, we look for new, improved NDE methods such as greater signal to noise ratio systems for ultrasonic and acoustic emission testing, microwave measurements of moisture and their relationship to material properties, scatter X-ray techniques, and inspection methods utilizing neutrons outside thermal energy region.

In no way should it be assumed that NBS expects to accomplish all this in isolation. New technique developments are being followed with full knowledge of related developments elsewhere. Calibration and standards concepts are being pursued in cooperation with professional organizations such as ASTM and ASME. Priorities in the NBS program are established with the assistance of professional societies and industrial and academic experts.

The objective of the NBS/NDE program remains the improvement of the reliability of materials and structures through standardized NDE measurements procedures. It is recognized that our role is to help industry develop methods for accurate and reproducible NDE measurements. Therefore, the NDE program is directed toward investigations of standards (both physical calibration standards and procedural documents such as recommended practices), characterization of instruments, development of improved techniques, improved understanding of the science underlying the measurement methods, and the assessment of the meaning of the NDE measurement on material performance. To accomplish this, a technical program has been started and strong interactions initiated with industry, technical societies, the university community, nonprofit research organizations, and government agencies.

Acknowledgments

The author is pleased to acknowledge helpful discussions with several NBS colleagues in the preparation of this report. In particular, the author would like to express thanks for assistance to George Birnbaum, Donald Eitzen, Curt Reimann, and George Uriano.

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Economic Benefits of Reliable Nondestructive Evaluation Standards

REFERENCE: Doherty, J. E., Baldwin, M. E., and LaGrotta, J. M., "**The Economic Benefits of Reliable Nondestructive Evaluation Standards**," *Nondestructive Testing Standards—A Review, ASTM STP 624,* Harold Berger, Ed., American Society for Testing and Materials, 1977, pp. 328–336.

ABSTRACT: The evolution of nondestructive evaluation (NDE) to its current sophistication has been long and involved. The primary driving forces in the evolution of NDE are derived from economic considerations; the primary concern is to drive the total cost of a product to a minimum. The interdependence of the inspection process and the production process is considered using a probabilistic outlook and some historical perspectives. A generalized discussion is presented to demonstrate how cost savings might be incurred by the introduction of a reliable inspection system. The value of reliable NDE standards in reducing inspection uncertainty and the impact of this uncertainty on the total cost of a product is discussed.

KEY WORDS: nondestructive tests, standards, economic analysis, cost control

Systems, machines, things, and components are inspected when initially constructed and during use to minimize risk of failure. Failures are costly because they are unexpected and because they can cause loss of life, production, and other components. We inspect, therefore, to minimize future costs. On the other hand, inspection sequences are costly to perform, and they increase costs when satisfactory items are discarded erroneously by an inspector. Therefore, inspection increases current costs. We are caught between these two cost drives, faced with making decisions about inspections and standards sometimes with little knowledge of how our decisions will affect the total cost. It is clear, however, that the proper inspection system is the one which will yield the minimum total cost. We would like to present a discussion of how nondestructive evaluation (NDE) standards are important in arriving at minimum total cost.

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Definition

Any discussion of standards should include some sort of definition of what a standard is and, as with many broad terms, there are many variants from which to choose. To those with strict views, a standard is simply a reference to which things are compared. To others more liberal in view, a standard is the description which enumerates and details those characteristics which are expected qualities. In the stict view, this description is the specification. The distinction between the standard and specification is difficult to establish for many people because of the way standards and specifications evolve. A little historical anecdote might demonstrate this more clearly as well as help lead into a discussion of how inspection and cost are related.

In the late 1930s and early 1940s, aircraft powerplants were piston engines. In those days, it was common to perform a one-shot inspection of the entire engine after assembly, that is, run it for a specific time and under specific power settings to provide adequate evaluation of parts under operating conditions. If parts did not fail, the engine was acceptable. Other examples of proof testing exist today in other industries. This method of quality control was satisfactory until the failure rate of the crankshaft in a high performance engine during the test run became large. The increased cost of teardown required a solution—the magnetic particle inspection (MPI) of the crankshaft before assembly.

This inspection was developed and evaluated only from known component experience. There were no previously developed laboratory procedures, specifications, or standards upon which to rely. To put it simply, the inspection was defined by results—successful engine run experience. A team would evaluate crankshafts with detected defects and establish accept or reject criteria of the component. The standards were defective parts which were too weak to make it through the initial proof test green run. The specification and the rejection criteria were defined in terms of that standard.

This example clearly shows that the distinction between specification and standard becomes clouded when inspections are evolutionary. There are no difficulties with distinctions until an inspection is formalized to a general application. This story has another important point.

Inspections may be instituted or changed because of economics. In the piston powerplant example, the change from a one-step inspection system to a two-step inspection system was made because the cost of overhauling engines exceeded the cost (probably by a good margin) of the new inspection step. In making the change, future expense was traded for an earlier one and by the exchange the total cost was lowered without changing (or more likely improving) the quality of the engines produced.

Two Important Inspection Parameters

But now to the real question at hand—what is the economic impact of having reliable or unreliable NDE standards? To be direct, an unreliable standard will increase the inspection uncertainty, and an increase in the inspection uncertainty may or may not increase cost. This statement will require some explanation.

There are two quantities which are very important in defining an inspection system: the inspection threshold and the inspection uncertainty. The threshold is the discrimination level or decision point which is set to discriminate between classes of things. In the simple case, it is a yes or no point; in the extrapolation, it may be a series of points allowing one to order a population into like groups. A measure of how well we can make this discrimination with a particular system is the inspection uncertainty for that system. For example, if we were sorting a population of balls into boxes of white ones and boxes of black ones, there would be numerous black balls in the white box and white balls in the black box if the inspection uncertainty were large. If the inspection were perfect, with no uncertainty, there would be no alien balls in either box. These two quantities, inspection threshold and inspection uncertainty, can have important implications on the cost to manufacture, the cost to use, and the cost to inspect. The detailed effect depends upon the time period over which the total cost is acccounted. Before considering the problem from a probabilistic cost vantage, an imagined hypothetical example which depicts a typical production inspection system will be helpful.

An imaginary foundry company is in the business of making manhole covers. It, like any company, is in business for profit. A prime factor contributing to how well a company like this foundry is performing is its manufacturing yield—the number of castings sent out the door as compared to the number of castings poured. Here, the yield is maximized by taking the attitude that if the manhole cover can take a few drops across the floor and be loaded on a truck then it has sufficient quality to meet the job. Here, the "inspection" is simple and the manufacturing yield is near 100 percent since very few pieces break in handling. It is clear that this foundry company is only concerned with what happens to its product while it is in the plant. It obviously gets very little feedback from its customers, and, therefore, the economics of the situation take on a myopic view. It is axiomatic that if they were to increase the threshold of their inspection, say, by intentionally dropping each manhole cover from 3 ft, they definitely would ship a better product but they also would just as surely decrease their yield. This foundry takes the cheapest way out, since there is no penalty or incentive requiring them to increase production cost. But now, what are the economic effects of inspection uncertainty on the operation of this foundry company?

The inspection uncertainty is a measure of the nonuniformity of the manhole cover inspection method. Each cover is not subjected to the same stresses as it is moved through the plant; some get "tested" thoroughly and others, a little less. Some covers will be shipped that should not have been and others that normally would have been shipped would not be. This variation or inspection uncertainty, on the average, will have no effect on the yield because there is an equal likelihood for a manhole cover to be over inspected or under inspected. There will be, however, considerable variance in the quality of the product that the imaginary foundry company ships. There are two points demonstrated by this example: (*a*) if a producer institutes a stricter inspection by changing his inspection threshold, he will ship better quality goods but he also will increase his costs because of a lower yield, and (*b*) if a producer decreases his inspection uncertainty, he will assure a more serviceable product without affecting his yield. This is an important conclusion since it implies that if inspection uncertainty were to be reduced *by improving inspection standards,* more reliable components can be had with *no effect on the yield* of the manufacturing process.

It is important to note that the view of inspection given here is not always correct. Fortunately, it is representative of most practical cases since in most practical cases the rejection rate is usually low and the defect distribution about the threshold level is essentially constant. This statement deserves clarification.

Inspection Model

In an inspection there are two factors other than the inspection threshold and inspection uncertainty that are important: the defect distribution and the noise or false defect distribution. These distributions are simply the number present or likelihood of occurrence for a given size defect (indication); both distributions are usually (but not always) monotonically decreasing functions with increasing defect size. Figure 1 shows schematically how these distributions as well as how the inspection threshold and uncertainty would appear in a typical case. The essential features are that the threshold is located at a defect size where the density of defects is low as well as where the density of defects is nearly independent of defect size. Under these conditions, the rejection rate will not be too large and the rejection rate will be independent of inspection uncertainty. The figure also shows the noise distribution to be significantly below the defect distribution at the threshold level but that it increases much more rapidly with decreasing defect size than does the defect distribution. This is indeed what is found usually; as the gain or sensitivity of an inspection is increased to look for smaller defects, a point is reached where the num-

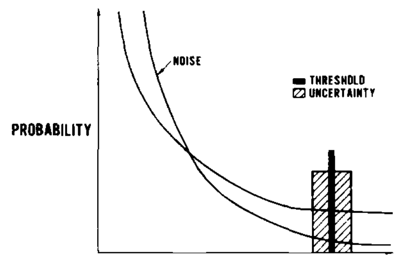

FIG. 1—*A model of a typical inspection. The probability of detecting a defect decreases with increasing defect size. The threshold is at a point in the distribution where the proability of finding a defect is relatively low—that is, the model depicts a system where the process yield is high as it is for most practical cases. The yield is independent of the inspection uncertainty because the defect distribution is relatively insensitive to defect size at the inspection level. A noise or false indication distibution is drawn to indicate a reasonable signal to noise distribution at the inspection threshold.*

ber of false signals generated by the inspection system itself far outweighs the number of expected defects; most inspections operate with a reasonable signal to noise ratio.

The model presented in Fig. 2 represents an example where if reliable *NDE standards were introduced* to reduce inspection uncertainty there would be *a higher quality product with no change in yield.* There are, however, other cases where this generality does not apply and a change in inspection uncertainty will effect the yield. For example, consider another process where the inspection threshold is at a defect size where the defect distribution is a rapidly increasing function. In this case, we are modeling a process where the rejection rate is high and the yield low (a poor process). Notice now that the inspection uncertainty has an effect upon yield also. The number of overestimates of defect severity outweighs the number of underestimates or, in other words, more good parts are thrown out than bad ones accepted. In this case there is a definite economic advantage for the producer to reduce the inspection uncertainty to increase his yield. The increased yield and resulting higher quality product represents a double advantage in having good NDE standards to minimize inspection uncertainty.

Diversion—Inspection For Process Control

This seems to be an appropriate place for a little digression. We have been reviewing how the general features of an inspection system affect production costs and, to put this discussion in a proper perspective, it may be of value to address the question of what is the function of NDE or quality assurance in production.

Most practical quality assurance operations are process control systems.

Their purpose is to provide the cost conscious manager with a measure of how successfully a process is producing good quality items. The rejection rate is the quantity which is important for process monitoring. The foundry company just discussed is typical of where the quality assurance system is really a process control system. The foundry manager knows that if the yield drops too low (that is, if the rejection rate increases), it is an indication that something is amiss and that various critical stages of the process should be reviewed. The foundry manager is more concerned about his yield than he is with the fact that he may be shipping more inferior parts (which is because of inspection uncertainty). It is important to note, however, that inherent in this manager's attitude is the assumption that when the process is working well and the yield is high the process is producing manhole covers of adequate quality. This assumption is typical for most of us since we usually build the quality in and not inspect it in. To do the latter would be far too costly because of poor yield.

The use of rejection rate as a process monitoring system is common. For example, consider the case of a computer-controlled automobile assembly plant. This type of plant is a large assembly line with smaller assembly lines feeding into it. Consider for a moment the difficulties in quality control; a misformed component or poorly assembled subassembly cannot be removed from any line for poor quality or the whole plant will be disrupted. The solution to this problem is that all parts are assembled into a car independent of their quality status, and each car carries a checklist where the quality of each item is indicated. At the end of the line when the cars are started, all those cars with checks indicating errors are put in a special area. How these cars are refurbished is another story, but the point of the example is simply that the plant manager counts the rejects—if they are too low, he speeds up the line, and if they are too high, he slows it down. His experience in how production rates correlate with yield allow him to optimize the cost factors.

It might be said that this view of inspection as a process monitor is all well and good for common everyday articles but what about those highly critical aerospace components and components for commercial airlines where a failure may have high visibility and be costly in dollars and lives. We would suggest that even in many of these cases, production inspections are still process monitors and that one still relies mainly on the processes. One endeavors to build the quality in rather than inspect the quality in. A simple case in point is turbine disks for commercial aircraft propulsion. An airliner has never been lost because of a turbine disk failure. The reason that these parts are so reliable is because the structural design and production process assures consistent homogeneous material. Rejection rates for material defects testify to this because they are very low even though each disk is examined thoroughly and carefully.

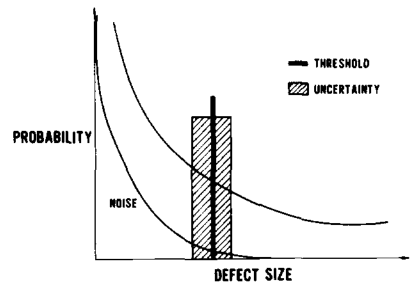

FIG. 2—*A model of an inspection where the process yield is low. In this case, there is strong incentive to reduce inspection uncertainty because inspection uncertainty will cause more good parts to be discarded than poor ones retained when the defect distribution is strongly varying. A noise distribution is shown also for completeness.*

What we have been trying to do in the last few paragraphs is build a case for the point of view that, in cases where one is concerned with primary costs (yield), it is far more effective to invest in developing a better process than it is to develop a better inspection. This is a very important operative statement, and it is a prime force in technology development. An example here may be useful.

One of the first major uses for titanium was for compressor components for jet engines. In the late 1950s, when the transition from steel to titanium components was being made, titanium was very expensive and of inconsistent quality. Titanium billet producers were required to inspect billets ultrasonically to a sensitivity equivalent to a No. 8 flat-bottomed hole. Service requirements demanded that inspection requirements be tightened by changing the inspection threshold to a level equivalent to a No. 3 flat-bottomed hole. This change in threshold initially had a profound effect on the billet producers' yield so that they had to improve the process substantially by going to double and triple melt procedures.

Contrary to all the predictions that the cost of titanium billets would increase substantially because of improved processing, the cost acutally did not change because the yield of the multimelt process was superior to that of the single melt process even with the more stringent inspection requirement. Needless to say, there were savings because of reduced scrappage and lower risk of field failure.

Long Term View

So far we have been focusing on cost pressures in primary production and ignored postproduction factors such as customer attitude and liability. The addition of these future cost factors underscores the importance of low inspection uncertainty and reliable NDE standards.

In most cases, a producer views with concern the successful application of his product because future business depends on satisfactory customer experience. It is not difficult to list examples where poor performance of a product caused significant increased user costs. These increased costs can produce impediments in the users mind when it comes time to reorder. Table 1 is a short list of cases where a failure has a large impact in terms of dollars. There are, however, multitudes of examples (zippers, shoes, seeds, etc.) where the dollars per event may not be as large, yet the results of failures eventually can be just as devastating to the parties involved. It is important for a manufacturer to have good NDE techniques with low inspection uncertainty (reliable standards) if post production cost factors are to be minimized.

TABLE 1—*Typical costs that might be anticipated if a common everyday item were to fail in service.*

Airliner	loss of revenue on N.Y. to Hong Kong flight	\$120 000
Auto steering gear	recent awards for loss	500 000
Power plant	cost to buy power normally produced by plant	10 000/day

Earlier when we were concerned only with local production factors (process yield) it was very easy to see the relationship between inspection factors and costs. Now, with the addition of future related cost factors, the establishment of an interrelationship is less direct. Although it is clear that we are concerned with a new "yield," one that is a measure of successful life after a use time, X, it is difficult to assess to what extent production changes are warranted to offset losses in the future.

It is possible to construct an analytical model that describes the interactive paths connecting liability, failure rate, and production that could be used to determine optimum production inspection requirements to minimize cost over any production-use cycle. The unfortunate difficulty is that to use these models, specific data on factors related to defect distributions, service use, etc., are required. These data are difficult to obtain without great expense. In fact in most cases it is difficult to establish actual failure costs in terms of lost production or lost ancillary components. It is true nevertheless that poor NDE standards in production quality assurance increase the risk of service failure. Unfortunately the cost relationships are difficult to establish *a priori* even though the causal relationship is clear.

Conclusion

What we have been talking about in this paper is the economic benefit of good quality assurance for NDE. Whether this quality assurance takes the guise of frequency standards, defect reference standards, procedural, or technique standards etc., we must agree that it is in our best economic interest to monitor how well our NDE systems are doing their job. We have shown that quality assurance for NDE can be had without any adverse effects on yield, the primary production cost driver. We have indicated also that the primary benefit of quality controlled NDE is reduced postproduction costs due to reduced service failures. These are good economic reasons for having reliable NDE standards.

Summary

This volume contains reviews, critiques, and general information on nondestructive testing standards. Background information on the standards preparation process and on the needs of various society and government organizations is followed by discussions of standards for specific nondestructive testing methods. These methods include radiography, ultrasonics, acoustic emission, liquid penetrant, magnetic particle, visual, optical, and leak testing. The final series of papers looks toward the future, for example, at needs for quantitative results and automated systems.

Appropriately, the first paper outlines the operation of ASTM Committee E-7 on Nondestructive Testing. R. W. McClung, chairman of that committee, describes the role the committee has played in putting forward nondestructive testing standards. The organization of the committee and the mechanism for producing standards are emphasized. The role of the American National Standards Institute (ANSI) and the International Standards Organization is presented in the paper by I. Resnick. The difficulties and the lengthy period of time to complete the requirements for an international standard are outlined. This initial series of papers also includes discussions of needs and procedures for nondestructive testing standards as related to the American Society of Mechanical Engineers (*ASME*) *Boiler and Pressure Vessel Code* and to military and nuclear inservice inspection applications. The important matter of nondestructive testing personnel and the certification of their qualifications is discussed by F. C. Berry from his vantage point of the American Society for Nondestructive Testing (ASNT) personnel certification experience.

Radiography standards are the subject of the next series of papers. The paper by John Aman addresses the many variables associated with radiography and cites the need for improved control and standards. Papers on image quality indicators, source calibration, real-time detection systems, film classification, reference radiographs, and neutron radiography give many additional insights into standards accomplishments and needs related to these special radiation areas.

The increasingly utilized techniques of ultrasonics and acoustic emission are discussed in a series of papers overviewed by J. E. Bobbin. Application areas are reviewed and the needs for quantitative, reproducible results are set forth in Bobbin's paper. The important role of the transducer is discussed by J. T. McElroy. The many variables, such as frequency, focus, damping and driving voltage, and the differing needs of industry make a standard calibration procedure for ultrasonic transducers difficult. The paper by C. E. Burley discusses another important aspect of ultrasonic testing, the calibration blocks. Burley believes that some of the variables now mentioned in regard to test block reproducibility can be traced to differences in instrumentation; certainly, the instrumentation and the blocks both have a strong influence on calibration. Efforts to improve reproducibility for the new technique of acoustic emission are described by W. F. Hartman.

The papers on liquid penetrants and magnetic particle testing were presented in brief form at the symposium and provided the basis for a panel discussion. Problems concerned with the multiplicity of standards and specifications are discussed, as are difficulties in differentiating between penetrant sensitivity and in determining realistic parameters for magnetic particle testing. The skill of the operators is cited as a major factor in achieving reliable and reproducible results in these methods.

The capacity of the human eye is examined by G. T. Yonemura in his paper on the consideration of visual testing standards. He calls for more data on the requirements of the varied uses involved in visual testing and suggests the need for the development of methods to test visual performance on a day-to-day basis. G. J. Posakony outlines the procedures used in ASTM Committee E-7 to generate a standard for a new nondestructive test method. He calls for more extensive participation in the voluntary standards process in order to shorten the time to generate new standards.

The final series of papers addresses the future and includes discussions of quantitative test results. These are needed if fracture mechanics analysis is to play a future role in quality control, as pointed out by E. T. Wessel. Concepts for quantitative ultrasonics standards are described in the paper by B. R. Tittman, D. O. Thompson, and R. B. Thompson. The theory of ultrasonic scattering from a spherical inclusion or void is well understood; experimental results can be checked on that basis. This advantage, plus that of no preferential orientation problems, offers an approach to an ultrasonic standard capable of quantitative results.

Standards and specifications for nondestructive testing have evolved over a long period of time. The papers in this volume begin a long overdue examination of these standards. The problems of multiple standards and the confusion and inefficiency that brings with it are cited many times. Also, problems of reproducibility for many methods are indicated because variables associated with the methods are not under sufficient control. It is good to have these problems brought out. It is hoped that this volume will provide a stepping-off point for solutions and future improvements in nondestructive testing standards.

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