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NEEDS FOR DEVELOPMENT IN NONDESTRUCTIVE TESTING FOR ADVANCED REACTOR SYSTEMS*

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ABSTRACT

The needs for development of nondestructive testing (NDT) techniques and equipment were surveyed and analyzed relative to problem areas for the Liquid-Metal Fast Breeder Reactor, the Molten-Salt Breeder Reactor, and the Advanced Gas-Cooled Reactor. The paper first discusses the developmental needs that are broad-based requirements in nondestructive testing, and the respective methods applicable, in general, to all components and reactor systems. Next, the requirements of generic materials and components that are common to all advanced reactor systems are examined.

Generally, nondestructive techniques should be improved to provide better reliability and quantitativeness, improved flaw characterization, and more efficient data processing. Specific recommendations relative to such methods as ultrasonics, eddy currents, acoustic emission, radiography, etc., are made. NDT needs common to all reactors include those related to materials properties and degradation, welds, fuels, piping, steam generators, etc. The scope of applicability ranges from initial design and material development stages through process control and manufacturing inspection to in-service examination.

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INTRODUCTION

Because of recognition of the important role that nondestructive testing has in assuring the quality and integrity of nuclear reactor systems, a report was prepared to delineate problems and indicate areas in which development should be accomplished. The report is a summation based on (1) the knowledge and experience of the author and the NDT development group at Oak Ridge National Laboratory (ORNL); (2) an extensive survey conducted among knowledgeable personnel (designers, fabricators, and NDT experts) from government, industry, and other sources; (3) previous reports that discuss NDT needs. This paper is an abbreviation of portions of that report.

Although emphasis was given to the Liquid-Metal Fast Breeder Reactor (LMFBR), attention was also given to the High-Temperature Gas-Cooled Reactor, and the Molten Salt Reactor. The general organization for this paper includes (1) general needs for improved NDT methods, techniques, and equipment; and (2) needs for components that are common or similar for different reactors. Fuel elements will not be included. This does not imply that fuel assay and safeguards technology are not part of the overall family of nondestructive testing.

METHODS-ORIENTED PROBLEMS AND NEEDS FOR NDT DEVELOPMENT

Needs Common to All Methods

Many of the recognized problems (or shortcomings) of the current state of technology in nondestructive testing are independent of any given reactor system or component. The needs are shared by many or all of the reactor systems and components. Therefore successful solutions to these problems will accrue directly to the benefit of any reactor system under consideration.

A Brief Look at Administrative Needs. Although the principal thrust of this paper is toward necessary research and development for nondestructive testing, this aspect does not cover all that is considered to be vital to a realistic and optimum use of the technology. Although no significant elaboration will be provided on the "administrative" or "software" side of NDT, brief mention will be made to provide a more complete coverage of the overall subject. For example, NDT has traditionally been limited by many to the detection of discontinuities in manufactured goods and, more recently, to the in-service examination of assembled products as a function of maintenance. The consideration of NDT should begin with the first stage of design to assure that the manufactured item can be inspected, both from the standpoint of its configuration and the relative accessibility in the assembled system.

Any necessary development of NDT methods or techniques should begin early enough on critical-path schedules to assure that the tools are in hand to be used in other developmental phases such as fabrication, new materials, etc. By having proper dialogue in these early planning stages among designers, materials people, and NDT personnel, the correct questions can be asked (and answered) about what properties need to be measured; e.g., is it density, presence of porosity, cracks or other discontinuities, dimensions, modulus, or some other. The early development and application of NDT is necessary for the establishment of correlations among the signals obtained, conditions of material producing the signals, and the effects of these conditions on the materials performance in service. Thus, this will not only provide useful data to further the development of materials or manufacturing processes, but will also provide the guidance for practical acceptance limits on the finished goods. Major benefits can be obtained through greater application of NDT for process control; e.g., the number of acceptable items will increase per unit of manufacturing, decreasing costs and improving delivery schedules.

Another administrative problem that plagues many organizations and fabricators is the lack of competent, qualified personnel. Since most of the NDT technology is people-oriented (and will continue to be for some time), the results of examination are heavily dependent upon the personal abilities, judgment, and interpretation of the operator. With expanding demands for NDT throughout all industry and limited educational opportunities for development of new personnel (primarily short courses for engineers and a few vocational schools for technicians), it is becoming a greater problem to assure that inspection organizations have the qualified people who can meet the certification requirements of most nuclear standards. This can, of course, affect the reliability of the NDT being performed. Among the several solutions to this problem are increased education and training to provide upgrading and a greater supply of competent personnel, and development of improved equipment, techniques, and technology to reduce the reliance on the skill and subjective reasoning of the operator.

Need for Improved Reliability and Quantitativeness. Frequently, as nondestructive examinations are repeated, different results are obtained within an organization or between separate organizations, e.g., between the seller and purchaser of material. This variability creates confusion, debate, commercial problems, and questions about safety of components and the reliability of the examination method. Since NDT is a system embodying people, materials, procedures, techniques, and equipment, the solution to the problems of reliability may take several forms. We have already noted the need for qualified people. The operators require written procedures that will assure an unambiguous understanding, which, when properly followed, will result in more consistent performance. Too often existing documents are not adequately specific and definitive and need improvement. We need an increased knowledge of the many variables in both techniques and equipment that can affect examination results so corrective action can be taken. To cite just one example in this section, the frequency spectrum in an ultrasonic pulse can vary significantly in an examination, and with inadequate knowledge of both the changes and the frequency response of allegedly similar transducers and instruments, variable results can occur. Studies should be performed to gain a better understanding of the statistical variability and reliability of various NDT techniques. For example, the Air Force has sponsored work on the ability to detect various size flaws using both penetrant and magnetic particles; a few other limited studies have been conducted. The task at HEDL on FFTF fuel cladding, in which statistical limits and control on ultrasonic testing were established, is an example of such work, which should be accomplished for numerous other applications. To enable fracture mechanics or other analytical tools to be used as a design method, one needs to know with higher confidence the lowest level of detection (smallest flaw that will *always* be detected) on a reliable basis (and if necessary determine what needs to be done to achieve higher sensitivity). In some instances it may be sufficient to have numerical confidence in the smallest flaw that will be detected 95% of the time, or 90% or even

50% of the time. Quantitative statements about reliability of present systems can be made only after statistically controlled studies; necessary improvements to less-than-adequate reliability will require appropriately directed development on the elements of the test.

A related consideration is the increasing necessity for more quantitative data from NDT. The technology has been directed toward the qualitative detection and location of discontinuities. However, there is an increasing need for upgraded capability to achieve quantitative measurement and characterization of discontinuities or other conditions. Some of the conditions contributing to this need include the advent of fracture mechanics to calculate the significance of flaws to serviceability; but successful application of fracture mechanics depends on a confident awareness of the exact size and orientation of a flaw that is detected (or a quantitative awareness of the size of the largest flaw that could go undetected).

Need for Improved Flaw Characterization. The NDT techniques are frequently comparisons of response between a known artificially produced artifact such as a drilled hole or machined notch and the detected unknown condition (and the responses are usually described in terms of that from the artificial rather than that of the actual flaw). As discussed in the previous section on quantitativeness, there is need for new and improved NDT capabilities to identify and interpret the responses in terms of the exact character of the internal condition. For example, when a flaw is detected during in-service inspection several immediate questions must be answered with confidence: What is it? Is is new? If old, has it grown? What is its exact through-the-wall dimension? How close is it to a surface? These are questions to which accurate answers must be provided, and technological development must be accomplished to achieve the desired status.

Need for Increased Computerization of Data. Another problem with broad-based application to many NDT methods and reactor components is that for increased need of computers or other advanced instrumentation for processing and analyzing data. Some of the technology may be available in other instrumentation or communications technology.

There are several aspects and time scales for such need and application. The earliest applications (and embryonic work has begun) is for simple data collection, processing (possibly enhancement), and analysis of voluminous data in production-type applications for repetitive work and to relieve the human operator. For fully successful application of computers to such go no-go evaluations, data collection and storage, the previously described needs for improved reliability and quantitativeness in techniques and equipment are obviously paramount.

The next stage of computer needs and application will include the extraction of more basic data from NDT signals (e.g., frequency spectra and phase of ultrasonic pulses) to allow more interpretation capability or pattern recognition. However, achieving this stage will require additional development of knowledge within the respective disciplines of ultrasonics, eddy currents, etc. Successful completion could, of course, do much to solve the aforementioned problem for improved defect characterization.

A third stage of computer development and integration in NDT that is ultimately needed is for the development of basic NDT equipment designed for direct computer-coupling (e.g., with full digital electronics) rather than simply attaching a computer to receive signals tailored for human interpretation. This design philosophy would allow more distortion-free data to be available for automatic, real-time processing, analysis, and interpretation. To cite just one benefit, in manufacturing the feedback in process control would do much to assure that only acceptable parts are fabricated.

Need for Improved Shop, Field, or Commercial Application. As techniques and equipment are developed in laboratory studies, these should be completely followed through so that the technology has ample opportunity to reach its full application on the production line, in the field, or in other appropriate areas. This will not only require extensive effort beyond the feasibility or demonstration stage, but will also require consideration for simplicity of operation or performance, for system reliability, and for economics.

Individual Methods

The previous sections on needs common to all methods of NDT should be kept in mind as the following sections on individual methods are presented. Although occasional brief inference may be made to previously cited needs, to avoid undue repetition no concerted effort will be made to assure citation on every method to which the general needs are applicable.

Penetrating Radiation. This method covers all application of x rays, gamma rays, and neutrons for qualitative imaging (e.g., radiography) and quantitative measuring (e.g., radiation attenuation). The most common application, radiography, has been widely used for years without significant changes. A major problem is the reliance on the human operator to make a subjective evaluation of the radiographic image of both the specimen and the image quality indicator (IQI), or penetrameter, used to assure the basic radiographic quality. Work is needed to reduce the human element and make the method more reliable and the results less subject to controversy. Potential approaches for accomplishing this are studies to improve the IQI and work on radiographic image enhancement. The American standard IQI is a thin shim or plaque containing cylindrical holes. It has decreased applicability for thin (less than 0.25-in.) sections and for assuring that narrow linear indications are visible. The European standard penetrameters use small-diameter wire to demonstrate image quality. These, too, have limitations. A fresh look should be taken at each one of these (and other) concepts in an attempt to improve the IQI. Radiographic image enhancement is a special case of the NDT data enhancement that was mentioned earlier. Sophisticated work has been accomplished using large computers as an outgrowth of the space program and photographic enhancement. Most of these efforts deal with reducing distortion, reducing noise, and sharpening edges. Beneficial results have been obtained, but large, expensive computer facilities are required. Less expensive approaches are needed that can be within the price range of most radiographic laboratories. The limited work with closed-circuit television for image enhancement needs to be expanded to achieve better image (not just the edge) enhancement, and further to automatic processing to simplify interpretation. Another enhancement approach that should be investigated is Fourier optical processing to accomplish frequency filtering similar to that performed with computers.

There is a need for improved techniques and equipment for performing radiography as a part of in-service inspection in a radioactive background. With the necessity to examine through both walls of pipe (frequently containing fluid) this could require higher energy sources than are currently available for field application. An alternative for "hot" radiography would be to develop techniques incorporating specimen shielding and slit scanning similar to that which has been used for hot-cell application.

Among other problems are needs for (1) improved techniques for dimensional measurements, (2) crack detection, (3) better guidelines for choice of radioisotopes or x rays, and (4) improved ability to ignore surface irregularities (such as weld roughness).

As cited in an earlier section, there is a need for more quantitative data and improved flaw characterization. Several developmental approaches that could help to achieve this with penetrating radiation include the aforementioned radiographic image enhancement, layer radiography (e.g., laminagraphy or tomography), advanced film densitometry, and direct measurement of the transmitted radiation with quantifying detectors (such as scintillators or semiconductors).

<u>Ultrasonics.</u> Many of the needs cited in the section covering problems common to all methods such as improved reliability, quantitativeness, flaw characterization, signal enhancement, and computerization of data are directly applicable to ultrasonics, and detailed discussion will not be repeated here. In addition to these general needs (whose solution would significantly upgrade the applicability and and capability of ultrasound) there are a number of specific needs, which in some particulars may be also related to the general needs. The recognized needs will not be presented in order of importance or priority.

Improved calibration techniques are needed. This is a multifaceted problem including the transducers, the electronic circuitry of the instrumentation, the physical material used as reference and transfer standards (test blocks containing mechanical flaws), and the assembled system with the attendant inspection procedures. The calibration procedures should include both the in-laboratory or bench-type techniques for preinstallation and periodic maintenance and the on-line, rapid recalibration of an inspection system to assure continued consistent performance.

There is a need for higher confidence and control on the size, shape, and direction of the ultrasound beam emitted from the transducer and projected into the specimen. Successful solution would increase the confidence in flaw location, in resolution of closely spaced reflectors, and in defect characterization. One approach that appears to have merit, based on the results of several investigators, is the use of multielement transducers with adjustable excitation for beam direction and control. However, further study on the concept is needed.

A better understanding of ultrasonic propagation and reflection is needed. One method of gaining an improved practical awareness is through the use of ultrasonic schlieren techniques. Studies should be performed with advanced schlieren systems to investigate the behavior of new-design transducers, and to study the interaction of sound with discontinuities in both transparent (e.g., glass) and opaque (i.e., metallic) specimens, thus gaining new insight about transducer design, ultrasonic focussing, transducer placement, and technique development.

Most current ultrasonic techniques use primarily the amplitude of the signal and time of arrival for interpretation, with only nominal attention given to the frequency and no attention to the phase of the signals. Investigations have shown that the spectral content of the ultrasonic pulses can vary and have a significant effect on the performance. The phase of reflected signals will be affected by the acoustic properties at the interfaces. Major effort should be directed toward gaining a better understanding of the role of frequency spectra and phase in ultrasonic nondestructive testing. The expected benefits would be the gaining of significantly greater information from the ultrasonic signal about the character, size, and orientation of reflectors, and improvement in the reliability of ultrasonic technology. Preliminary studies have already demonstrated the feasibility of such endeavors.

The successful utilization of more data (e.g., for production, in-service inspection, or the above-mentioned frequency and phase) would increase the need for improved instrumentation to simplify processing of the signal (perhaps with computers) without the distortion that frequently occurs with present-day devices. New instrumentation should probably be based on digital circuitry to enhance the possibility that the real signals are computer compatible for processing, analysis, and storage.

Some of the previously cited problems of quantitative measurement, characterization, and location of flaws and test reliability are particularly troublesome in thick sections (e.g., greater than 4–6 in.). For example, based on in-service inspection studies in light-water reactor pressure vessels, one of the major problems is confident measurement of the through-the-thickness dimension of detected flaws. Work is needed to overcome these limitations.

A new technological approach to ultrasonic testing is acoustical holography, a technique for qualitative scanned recording of phase and amplitude information to allow reconstruction of an acoustic image with three-dimensional information. This allows qualitative visualization of a flaw (or other reflector) within an opaque specimen. Beneficial studies with the method should include increasing the examination speed and application to a large number of specimens containing actual flaws.

Acoustic Emission. In recent years there has been a tremendous upsurge of interest in and application of acoustic emission (AE) technology to monitor deformation and crack propagation or other stress-wave-emitting phenomena in a variety of materials and configurations. The several manufacturers of commercial equipment provide systems for qualitative detection and location of emitting sources. However, study is needed to obtain a better understanding of the the significance of the emission and an improved capability for quantitative interpretation of the signals in terms of, for example, flaw growth, deformation, or other material conditions. One current limitation on the interpretation capability is that the signals are frequently modified by the frequency response of the detector so that the actual characteristics of the event are obscured. A better understanding is needed of this as well as a determination of optimum processing of the received data (i.e., event counting, energy integration, etc.). In common with most NDT methods improved calibration procedures are needed to check the operation of the system. Improved sensors and mounting techniques are needed that have been demonstrated to be capable of operating for years at elevated temperature and in a radiation environment. As an in-service inspection there must be knowledge developed about the effect of material degradation (e.g., embrittling, corrosion) on the initiation and propagation of AE events. Acoustic events have been demonstrated to have benefit during the hydrostatic testing of pressure vessels, but significant application to field-type installation is needed to gain experience and confidence. There is controversy over the applicability (or generation of signals) in austenitic stainless steels at about 500°F. For example, these reservations coupled with the low operating pressures raise questions about the benefit for monitoring breeder reactor vessels. Investigations should be made on stainless steel to resolve this question. Signal enhancement techniques are needed to improve the signal-to-noise ratio, and permit more quantitative data. Extensive application of AE on reactor components should be made to improve the quantitative and qualitative aspects and to gain a fuller appreciation of the limitations and impediments to the method. Application studies should be made with various welding processes because of the potential to serve as a real-time process control monitor, detecting flaws as they are created.

Eddy Currents. As with ultrasonics many of the common needs are also applicable to eddy-current technology; e.g., needs for reliability, quantitativeness, flaw characterization, signal enhancement, and data computerization. The large number of parameters that can affect a simple examination lead to the need for techniques that can allow discrimination and separation of unwanted variables from desired signals in both simple and complex structures. Directions for solutions include (1) development of improved understanding of the quantitative theory, (2) development and improvement of design technologies applying the theory of the electromagnetic induction process, and (3) the development of practical instrumentation capable of performing simultaneous interrogations at several frequencies (by multifrequency or pulsed techniques) and concurrently processing the multiparameter signals to isolate the desired data. Other needs are for improved measurement of flaws and characterization (and identification) of various discontinuities, including intergranular attack, tubing wastage, etc. With many reactor components being constructed of ferromagnetic material, there is a need for technique development toward eddy-current examination of such materials (despite the high permeability) for surface and near-surface flaws. For in-service examination there is a need for development to allow performance at elevated temperatures and in the presence of radiation. To enhance the application of eddy-current techniques both for manufacturing and in-service inspection, there is a need for simpler, more reliable instruments to be developed as well as improved calibration and procedures to assure proper functioning of this inspection system.

Liquid Penetrants. The developmental needs for the relatively simple penetrant techniques are significantly less than for the more sophisticated methods, but some of the needs are similar. For example, there is a need for improved techniques for checking the performance and sensitivity of a penetrant system. Since a requisite for the examination is that penetrant flow into the discontinuities, there is a need to assure that the flaws are not already filled with another substance (perhaps even the cleaning solution). There is a need for penetrant materials that can be readily used at high temperatures (e.g., 400–500°F) for welds that must be maintained at a preheat temperature. A study should be performed to determine if residual penetrant (even containing limited halogens) after an examination can have an adverse effect on subsequent welding or service.

Magnetic Particle Examination. The principal needs of magnetic particle techniques are for calibration procedures and standards to confirm the sensitivity and performance of the system, and development to achieve quantitative results in addition to the qualitative response currently obtained.

New Technology. The preceding sections have dealt with needed improvements to methods that are currently recognized and used for NDT. There needs to be continued, long-range study on new methods that have the potential for problem solving as a supplement to existing technology. To cite only a few, consideration should be given to exoelectron emission for stress and fatigue studies, Barkhausen noise, magnetoabsorption, Mössbauer techniques, optical holography, and microwaves. Some of these have had success in laboratory studies but limited success on real world samples because of a lack of preservice characterization or history on the tested items. With the increased emphasis for quality assurance, archive samples, and material traceability, the potential is now much greater for preservice characterization and subsequent detection of change due to deformation, degradation, flaw initiation, corrosion, or other undesirable condition.

Thermal techniques have also shown considerable potential for materials evaluation, but additional work is needed for improved techniques. In particular, study is needed to alleviate the problems due to variable emissivity without the necessity of painting the object black (the current practice). Tests at multiple wavelengths may resolve this problem. Thermal surface impedance techniques also show considerable promise for extracting additional data from a thermal examination (an analog to eddy-current technique), and further study should be performed. Because of the dependence on subjective interpretation of magnetic particle examination (see earlier section) there is a need for investigation of other magnetic techniques for applications to surface and near-surface examination of ferromagnetic materials. The techniques should include instrumented detection techniques for leakage flux to provide more quantitative outputs for flaw evaluation. Other magnetic techniques should use measurement of coercivity, permeability, or other magnetic properties as a tool for characterizing the material for such properties as hardness, heat treatment, and dimensions.

NDT NEEDS FOR MATERIALS AND COMPONENTS COMMON TO MOST REACTORS

This section is divided into two major parts: (1) general NDT needs that are related to the material of construction and may be applicable to several components and (2) the needs that are more particularly applicable to specific components. In either case the needs are generic to several (or all?) reactor systems.

NDT Development Needs Oriented to Materials for Reactor Usage

This section will include discussions of needs for techniques for measuring material properties, monitoring degradation, welds, and alloy identification.

Materials Properties and Degradation. There is a general need for development and application of NDT technology for the measurement of materials properties. There are at least three broad aspects of this need: (1) as an aid to materials characterization (e.g., in heat-to-heat or heat treatment variations), measurement of properties on actual structures to be used, minimizing destructive analysis; (2) determination of the degradation or loss of desired properties in service to enable a decision for continued service; and (3) determination of the effect of the change in properties or degradation on the performance of the NDT for overall integrity. Among the properties that could be measured are modulus, density, strength, (e.g., with appropriate correlations in graphite, concrete, or other brittle material), electrical conductivity (and with appropriate correlation the hardness of metals), and magnetic permeability. Included in conditions contributing to degradation of material properties are embrittlement (due to creep or irradiation), sensitization (making the material susceptible to intergranular attack), corrosion, deformation or other strain, creep, onset of third-stage creep, swelling, carburization, and decarburization. Each of these undesirable conditions needs to be detected (and measured) to assure that premature or unexpected failure does not occur. NDT techniques need to be developed to assist in-service detection and measurement of these conditions. In some instances it may be necessary to nondestructively detect conditions leading to degradation. For example, unknown residual stresses can contribute to premature failure, creep, or deformation. Surface contamination and subsequent elevated temperatures can lead to intergranular attack or stress-corrosion cracking. Appropriate development of NDT techniques should be conducted to detect the problem before the adverse effects occur.

Welds. Welding is a method of joining that is common to most components of most reactor systems. The several needs for NDT development are therefore common. One of the problems centers around the occasional use of the wrong welding electrodes. The solution is probably a combination of improved NDT technology to verify the identity of the welding rod at the vendor, in the fabrication shop, and in the field as well as improved quality assurance (QA) procedures and control to prevent the weld being made with the improper electrodes, leading to inadequate strength and cracking. It has been suggested that approximately one-half of the bad welds can be traced to inadequate QA control. A common examination technique for thick multipass welds is to use liquid penetrants at various stages of the fabrication. But there is concern that the residual penetrant material can be a contributor to faulty welds in subsequent passes. This should be investigated and, if true, supplementary development is needed to allow performance of a noncontaminating examination at the desired intervals. Since some welded materials (for example, high-chromium steels) are not permitted to be cooled before postweld heat treatment, there is a need for NDT techniques (e.g., a high-temperature dye penetrant, ultrasonic, or other) that can be performed at the elevated temperature so defects and other undesirable conditions can be detected before the heat treatment. In addition, techniques (e.g., thermal NDT techniques) are needed that can provide accurate knowledge of the preheat temperatures and cooling rate for those high-chromium (9–12%) steels. The ASME Code Case 1594 requires double volumetric examination of the welds, allowing in some instances (e.g., in austenitic stainless steels because of problems with ultrasonics) two radiographic techniques at different angles to satisfy this requirement. Because of the disagreement over the validity and efficacy of the special radiographic requirement, a developmental study should be performed to base the requirement on demonstrated facts or to recommend changes.

As mentioned in the discussion on acoustic emission, promising studies have been conducted in which the welding process was monitored. In many instances the signals received were correlated with the overall integrity of the joint and the presence of discrete discontinuities. In different materials the responses were different (i.e., high emission rate in some materials indicated bad welds, in others good welds). Additional work is needed to establish useful process control instrumentation to increase the possibility that only good welds will be made (or corrective action initiated early for out-of-control conditions).

Because of the importance of the nondestructive examination of austenitic stainless steel weldments, this problem will be considered in an independent section.

<u>Austenitic Stainless Steel Welds.</u> A current and widely recognized problem is the volumetric examination of coarse-grained stainless steels, particularly welds. A principal reason for the problem is the difficulty in applying ultrasonic techniques because of the large, variable attenuation and the high level of noise encountered during an examination. There are widely divergent views ranging from optimism that existing techniques are applicable to pessimism whether ultrasound will ever be useful for stainless steel welds. However, the widespread use of such materials, and the need

for techniques other than radiography (because of the limited capacity of radiography for crack detection and the difficulties of application to in-service inspection) make this an important problem for investigation. The fact that occasional welds can apparently be ultrasonically examined lends confidence that development should be beneficial. Because of the multifaceted nature of the problems, a successful solution will probably require a well coordinated program with approaches from several directions. For example, since some (a few) stainless steel welds can be examined, there is a need for a joint effort with welding development to determine the welding practice, microstructure, or other conditions that can optimize service and inspectability. There is an attendant need for techniques to measure grain size and orientation in weldments since these can affect both the inspection and performance of the weld. The higher-than-average ultrasonic attenuation in austenitic welds fosters a need for techniques that can overcome this problem. The use of angle-beam longitudinal wave ultrasound has enjoyed limited success because of longer wavelengths and decreased sensitivity to the anisotropy in the grains. Other potential approaches (not to be considered exhaustive) include the use of lower frequencies (development will be necessary to overcome usual decrease of sensitivity and resolution with increased wavelength), development of techniques for increased pulse power, and the use of amplitude-insensitive frequency analysis techniques. If the attenuation continues to be a variable despite metallurgical studies, there is a need for techniques to recognize the change so that appropriate adjustments in calibration can be made during the examination.

The problem of excess noise from austenitic weldments also needs study to reach a solution. Potential avenues (again not exhaustive) include the study of focussing of ultrasonic beams, the use of frequency analysis, advanced data processing to improve the signal-to-noise ratio, artificial aperture scanning techniques that integrate the signals over an area of scanning (i.e., similar to acoustic holographic methods), and advanced imaging techniques.

Multiparameter eddy-current techniques should also be studied for application to base metal and welds to detect and measure near-surface flaws, ferrite, and heat treatment condition.

As mentioned in the discussion on acoustic emission, there is question about whether the ductile stainless steel welds will emit signals during deformation or failure. Sufficient study should be performed to satisfy this question because of the high current interest (or push) to use acoustic emission techniques for in-service inspection.

Alloy Identification. An occasional problem when more than one material may be present on a site is the inadvertent mix-up or loss of identification. In such cases there is a need for techniques to provide identification or verification of the proper alloys. This was briefly mentioned as a need for welding electrodes in the welding section, but it is common to all materials. Partial solutions have been achieved through the use of eddy currents (measuring or comparing characteristic electrical conductivities), x-ray fluorescence, thermoelectric properties, and chemical spot tests. The most difficulty is normally encountered in austenitic stainless steels because of the range of allowable chemical compositions and (for eddy currents) overlapping ranges of electrical conductivity. A coordinated effort is needed to develop uniform high-confidence, field applicable techniques and equipment to provide greater assurance that the correct materials are always used.

NDT Development Needs Oriented to Components for Reactors in General

This section is intended to address those needs for NDT development that are the same (or similar) for most advanced reactors.

Design and System Monitoring. As mentioned earlier under Administrative Needs, there must be closer cooperation and coordination between the designers and the NDT personnel. Among the several reasons are the assuring of adequate accessibility to the portion of the component or assembly requiring examination (both in manufacturing and in later in-service inspection) and the enhanced probability that a simple (or existing) examination technique can be applied. Both of these benefits could decrease the need for NDT development applied to specific hardware. Too often the consideration of nondestructive examination is too late (if at all), and expensive development of techniques and mechanical devices is required (or the benefits of NDT are sacrificed). For those items that must be designed and constructed so certain areas needing examination are truly inaccessible, consideration should be given to the design and implantation of fixed sensors (e.g., ultrasonic transducers) which with associated circuitry can be tailored to the specific interrogation. This will require the development of high-reliability transducers and associated devices that can withstand the environment for the life of the components. Rather than have the broad flexibility and versatility that are common to most NDT equipment, these systems could be designed with a "one-track mind;" e.g., concerned only with recognizing a specific signal pattern on a go no-go basis.

In a continuation of this line of thought, more on-line interrogation is needed for the proper functioning of entire components or systems; e.g., as a part of preventive maintenance using signature analysis techniques (thermal, mechanical, acoustic, electromagnetic) to monitor the continued health and proper functioning of items such as pumps and fan bearings. This is in addition to the discrete interrogation using more conventional methods of inspection to detect flaws or other degradation in the structural materials. The performance monitoring would confirm design data and monitor changes in service that could lead to failure. For continuous in-service monitoring capability (as opposed to periodic examination), there is a need for long-life sensors, environmental resistance, and high-confidence calibration techniques to assure factual monitoring.

In-Service Inspection. It is widely recognized that in-service inspection is required to assure the continued integrity of the reactor system. Many of the needs may be peculiar to specific components or reactor systems but a few are common to all. Because of the frequent requirement to perform the examination remotely due to the temperature, irradiation, or other adverse condition, improved devices and techniques are needed to minimize the manpower exposure and to increase the confidence, reliability, and significance of the examination. Heavy reliance is being placed on ultrasonic and acoustic techniques. Investigations and development should be accomplished to allow the extensive use of other methods (e.g., penetrants, eddy currents, and radiography) in the remote adverse environments.

Tubing. Much tubing is used in a reactor system for steam generators, heat exchangers, fuel cladding, etc., and there must be assurance that high integrity is achieved during manufacturing and maintained during service. Good inspection techniques are available for tubing inspection, but improved capability and conversion of laboratory technology into production procedures are needed. As discussed under general needs for NDT methods, there must be improved reliability and quantitativeness in the applied techniques. Developments are needed to allow more reliance on eddy-current techniques for high-speed examination of tubing. As part of this development there must be improved capability for (1) measuring flaw size, (2) characterizing defects, and (3) isolating noise (signals from insignificant variables) that can arise, e.g., as permeability variations caused by localized cold work during straightening of stainless steel tubing. Improvements are also needed in production inspection techniques using ultrasonics to improve the capability for (1) detecting small rounded flaws that are occasionally being overlooked, and (2) determining actual size and orientation of the flaws.

Most tubing specifications establish acceptance (or rejection) levels based on a finite size of flaw regardless of the relative wall thickness at the position of the flaws. Yet studies on the significance of flaws in tubing have indicated a first-order effect that tube strength in ductile materials is based on the residual wall thickness. Thus with tube wall eccentricity a flaw in the thick section could be innocuous, while the same size flaw in a thin section could be cause for failure. For more realistic specifications and to decrease unnecessary rejections, there should be an investigation and, if feasible, a development of inspection techniques that would determine residual wall thickness.

In addition to the usual application of NDT to detect flaws, development should be accomplished to allow nondestructive characterization of tubing materials for manufacturing variability — e.g., measurement of cold work, anisotropy, and grain size. Further comments on the needs for NDT of tubing are in the section on steam generators.

Valves and Pumps. Allegedly pumps and valves have been the major cause of aggravation, problems, and downtime in operating reactor systems. This should generate wariness for advanced reactor systems. Improved volumetric examination procedures (e.g., radiographic and ultrasonic) are needed on the thick-section bodies and impellers for both manufacturing and in-service inspection. Also important (and difficult to examine) are the heavy welds that join the units to the piping system. In-service examination for internal components such as impellers and valve seats may require development of unique NDT devices and techniques to allow valid application in awkward (almost inaccessible) locations. The thickness and bonding of hardfaced valve seats needs to be monitored for both manufacturing and in-service inspection.

Steam Generators. The history of steam generators in power generating systems indicates that leaks between the primary and secondary fluid are almost an accepted fact of life. When water is the common fluid the problem of leaks creates inefficiency, increases down-time at maintenance periods to find and plug the leaks, and requires initial overdesign to allow tubes to be decommissioned without reducing the capacity of the unit below that required. The leaks are aggravating, at times expensive, but in general there are no drastic side effects. However, when different fluids are used in the primary and secondary circuits (e.g., sodium and H_2O, helium and H_2O, molten salts and H_2O) the leak and subsequent mixing can have much more severe consequences as a result of interaction between the fluids (for example, a sodium-water reaction) or as a consequence of the leaking fluid attacking other portions of the system [for example, (1) the sodium-water reaction products leading to caustic corrosion and stress-corrosion cracking in the steam generator, or (2) steam leakage in a gas-cooled reactor causing attack on graphite components]. With the tubing being the minimum membrane separating the two fluids, the greatest concern and need for improved nondestructive examination methods is for tubing and the tube-to-tubesheet joints. With recent recognition that very tiny leaks (below the normal detection sensitivity for tubing inspection) can rapidly grow in service, there is now a new need for higher sensitivity examinations for short, deep flaws (leaks or incipient leaks) in critical tubing; and the development of the higher sensitivity techniques must include the capability for discrimination from long, shallow, acceptable flaws and high-speed performance to keep the costs down. For incipient leaks, the prime candidates would include advanced ultrasonic and eddy-current techniques; for existing leaks, additional approaches include tracer gases and acoustic techniques. The tube-to-tubesheet joints are also important as potential leak sites. For the commonly used face-side welds, the current technology and application provide only marginal examination (usually visual or penetrant techniques to detect flaws on the outer surfaces and occasionally helium leak testing to find leaks that are open at the time of examination). Although the orientation of the fusion zones and the configuration of the weld reduce the potential for further examination, improved techniques can and should be developed to increase the confidence in the integrity of the joints. Depending upon the exact details of a joint design, beneficial advanced techniques could be developed using radiography (with a miniature radiation source in the bore of the tube), high-resolution eddy-currents, or finely focussed ultrasonics.

A major need is for improved technology for the in-service examination of the tubing and tube-to-tubesheet joints to detect incipient failure or, after a leak, to identify and and characterize the leak source for isolation of the tube.

Let's consider an active leak first. There are several instrumental approaches for monitoring the fluids for evidence of a leak (e.g., detectors of moisture, hydrogen, oxygen, and helium), and such "sniffing" systems will not be included in this paper. However, acoustic noise detection should be considered and developed as a complementary mode of leak detection. The active leak will produce acoustic signals (1) as a function of fluid motion through an orifice (the leak) and (2) as bubbles of leaking gas form and collapse in a liquid (either as a simple mechanical action or as a result of chemical reaction). For use as an active, on-line monitoring system to detect and localize (by triangulation) the initiation of a leak, it will be necessary to develop a system that can function despite the noise associated with an operating steam generator and will filter or otherwise discriminate between leak signals and normal background noise. If the latter is proven to be impractical, the developed acoustic system could have potential for localizing a detected leak in a static system by using a pressurized inert fluid in one side of the system to generate noise as it is forced through the leak. Techniques should also be developed for examining localized tubes individually (for example, with tracer gases, acoustic techniques, high-resolution ultrasonics, or eddy currents) to locate and characterize the leak — determining if it were caused by a crack, hole, general weld thinning, or other cause — as a aid to assessing the probability of reoccurrence. Of course, examination of surrounding tubes for damage is also necessary.

For both leaks and incipient leaks (ultrasonics and eddy-current development are recommended for the latter), development is needed to assure the capability to perform high-sensitivity high-resolution examinations despite the presence (and inspection handicaps) of external tubing supports and baffles, thick tubesheets, limited accessibility, and the frequent curves or bends in the tubing. The use of ferromagnetic materials and duplex tubing increases the inspection problems requiring solution. As discussed previously in the section on Methods-Oriented Needs, development of techniques for signal enhancement, quantitative reliable defect characterization, and computerized processing and storage of the data will be necessary not only because of the voluminous data accumulated during an examination but also because of the need for comparison between successive examinations.

Piping. The principal needs for NDT development recognized for piping systems include improved techniques for installation welding, in-service inspection of both pipes and welds, and — when remote maintenance and replacement of piping or components are required — the remote inspection of the replacement welds.

With the trend toward automatic pipe welds, there should be adequate development to allow the same type of automated mechanism to be used for high-confidence nondestructive examination of the joint using ultrasonic and eddy-current techniques immediately after the welding process.

For in-service examination more sensitive techniques are needed for the detection of stress-corrosion cracking in stainless steel piping, particularly at the welds. A current inspection problem (in addition to those cited earlier) with stainless steel welds is that the rough inner surface at the weld creates noise and impedes interpretation. More discriminating ultrasonic techniques are needed and improved capability to perform radiography with improved sensitivity in the field on radioactive specimens would be beneficial. The detection of propagating cracks is extremely important, even with materials that allow the consideration of the "leak before break" philosophy.

For remote inspection of remotely repaired welds, one needs automated examination systems that may be similar to the mechanized automatic system discussed for installation welding or in-service inspection, but probably with a greater tolerance for the environment (temperature, radiation, etc.) that makes the remote operation mandatory.

Pressure Vessel. Because of the diverse nature of pressure vessels for different types of reactors, discussion of needs should be limited to the specific reactor. However, there are some generic problems. For example, the pressure vessels are inherently very large units. Their size creates problems and needs for improved technology to perform volumetric examination. Residual stresses can be an important factor to the vessel, but the current examination technology is inadequate to detect and measure such stresses. Despite the very large size of the vessels, certain areas may need examination with extremely fine detail. Improved large-scale examination or screening techniques are needed to assure that the correct localized areas are identified.

SUMMARY AND CONCLUSIONS

An extensive (but not exhaustive) survey has been conducted of needs for NDT to be developed for advanced reactor systems. The findings have been divided into several major sections: (1) needs for upgrading of nondestructive testing and the respective methods that are commonly applicable without regard to specific reactor systems or components, and (2) needs that are related to materials or components for reactors in general and are not peculiar to any reactor.

Although this paper is a resultant from a multifaceted survey, the author recognizes that continued effort would probably uncover additional needs that have not been cited. Repeated conversations with the same interviewees would probably disclose additional thoughts as fresh experiences (and problems) occur. Further, it is recognized that many of the NDT problems have not yet surfaced because of the preliminary stage of design or planning for many of the components. For these reasons, this paper should be recognized as a first effort, and as a viable document with a continual need for review and an occasional need for updating. It is hoped, with a better definition of the needs, that practical solutions can be obtained, affording significant improvements in the safety, integrity, performance, and availability of advanced reactor systems.