AGING MANAGEMENT OF MAJOR LWR COMPONENTS WITH NONDESTRUCTIVE EVALUATION


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ABSTRACT

Nondestructive evaluation of material damage can contribute to continued safe, reliable, and economical operation of nuclear power plants through their current and renewed license period. The aging mechanisms active in the major light water reactor components are radiation embrittlement, thermal aging, stress corrosion cracking, flow-accelerated corrosion, and fatigue, which reduce fracture toughness, structural strength, or fatigue resistance of the components and challenge structural integrity of the pressure boundary. This paper reviews four nondestructive evaluation methods with the potential for in situ assessment of damage caused by these mechanisms: stress-strain microprobe for determining mechanical properties of reactor pressure vessel and cast stainless materials, magnetic methods for estimating thermal aging damage in cast stainless steel, positron annihilation measurements for estimating early fatigue damage in reactor coolant system piping, and ultrasonic guided wave technique for detecting cracks and wall thinning in tubes and pipes and corrosion damage to embedded portion of metal containments.

The microprobe measures the local mechanical properties, including yield and ultimate strengths, flow curve, and Brinell hardness, at a point on the surface of a component. The microprobe has been used for characterizing the heat-affected zone of the pressure vessel weld. These data can be correlated to Charpy V-notch energy and fracture toughness. Since the microprobe test requires only a small amount of material, it can be useful during the current or renewed license period when sufficient material is not available for the reactor vessel surveillance program.

The magnetic method uses an ultrasensitive magnetic sensor to measure residual magnetization and coercivity in thermally aged cast stainless steels. Available data suggest a possibility of correlating these measurements with the mechanical properties of thermally aged components. These methods and the stress-strain microprobe can be used for characterizing the spatial variation in the statically cast components, such as PWR hot-leg elbows and pump and valve bodies.
Positron annihilation measurements use Co-58, deposited in the corrosion layer on the inside surface of the primary coolant piping, as a positron source. Because positron annihilation occurs near the surface, it is possible to make positron annihilation measurements to estimate the fatigue damage near the inside surface of the primary coolant piping.

An ultrasonic guided wave technique has an ability to inspect the entire wall of a long length of tubing or piping. This technique has a potential for rapid detection of a circumferential crack in a steam generator tube and wall thinning in feedwater and main steam line piping without removing the insulation over most of the inspected length. This technique may be further developed for inspecting inaccessible locations such as an embedded portion of the metal containment and detecting thermal fatigue cracks in the piping base and weld metals.

INTRODUCTION

Materials used in major light water reactor (LWR) components are subject to aging that degrades their mechanical properties during long-term service. As the operating reactors age, degradation raises concerns about structural integrity of components and, therefore, the safe and economical operation of both pressurized water reactor (PWR) and boiling water reactor (BWR) power plants. The degradation mechanisms of significant safety and economic concerns include radiation embrittlement of reactor pressure vessels, stress corrosion cracking of vessel internals and steam generator tubes, thermal aging of cast stainless steel components, thermal fatigue of branch lines, flow-accelerated corrosion of carbon steel piping, corrosion of embedded portions of metal containments, and aging damage to concrete containments. Some mechanisms have a potential to become life limiting for the operating power plants. Effective management of several of these degradation mechanisms has been identified as open issues between Nuclear Management and Resources Council (NUMARC) and U.S. Nuclear Regulatory Commission (USNRC) (Regan et al. 1996).

Structural integrity of the aged LWR components is difficult because the reliable estimates of degraded materials properties are not available and the presence of structural defects such as flaws and wall thinning can not be characterized reliably and/or economically using conventional inspection techniques. Destructive testing may be used to determine the materials' properties; however, it provides limited benefits because only a small amount of material can be practically removed from the operating component or structure, subsequent repair could introduce additional aging concerns, and the locations experiencing significant aging damage may not be accessible. Therefore, surveillance programs and laboratory-based correlations are generally used for estimating the mechanical properties of the aged components. However, these estimates involve significant uncertainties. Safe and economical operation of power plants for an extended period of time requires more reliable and accurate estimates of mechanical properties. The nondestructive evaluation methods can potentially provide such estimates by in situ assessment of aging damage in the major LWR components.

Conventional inspection techniques have been reliable in characterizing most, but not all, defects in components. In addition, these techniques are not economical when a defect location is not relatively
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well identified or a length of piping susceptible to damage is large. The global inspection methods, when used along with the conventional methods, have a potential for providing economical in-service inspection of certain power plant components.

Nondestructive evaluation methods include testing techniques for directly estimating mechanical and fracture properties, material characterization techniques for predicting the microstructural changes that precede or are associated with the aging degradation of interest, and inspection techniques, especially global inspection techniques, that can reliably and economically characterize safety-significant defects. Each method has its own advantages and limitations. Therefore, we propose a combined use of several nondestructive methods for a comprehensive, quantitative, in situ characterization of the material condition of the aged major components.

This paper reviews four nondestructive evaluation methods with a potential for in situ assessment of aging damage, including one test technique, two material characterization techniques, and one inspection technique. The test technique includes use of a stress-strain microprobe for directly estimating mechanical properties of reactor pressure vessel and cast stainless steel materials. The material characterization techniques include magnetic techniques for estimating thermal aging damage in cast stainless steels, and positron annihilation measurements for estimating early fatigue damage. The inspection technique includes an ultrasonic guided wave technique for detecting stress corrosion cracks in steam generator tubes, thermal fatigue cracks in piping welds and base metal, wall thinning in feedwater piping caused by flow-accelerated corrosion, and wall thinning of embedded portions of the metal containments caused by corrosion. These methods are at different stages of development. The current status of each method and its advantages and limitations are identified.

**STRESS-STRAIN MICROPROBE**

The stress-strain microprobe uses a patented, automated ball indentation (ABI) technique and provides a direct, local measurement of mechanical properties including yield strength, flow curve (post-yield behavior), strain hardening exponent, strength coefficient, ultimate tensile strength, and Brinell hardness (Haggag 1989). The microprobe measurements may be correlated to Charpy energy and fracture toughness. The microprobe has been used for measuring the mechanical properties of several different materials including carbon steel, low-alloy steel, and austenitic stainless steel base metal, weld metal, and heat-affected zone. The technique is essentially nondestructive because no material is removed from the surface tested, only a smooth shallow indentation (smaller than 0.3 mm) is left on the surface at the end of the test. The indentations are performed with a spherical, tungsten carbide indenter with a diameter in the range of 0.25 to 1.57 mm. The microprobe system is equipped with an environmental chamber so that the laboratory tests can be performed in the temperature range of -200 to +350°C.

The microprobe system is based on the principle of strain-controlled multiple indentations at a single location on a polished surface of a test specimen. The indentation depth is progressively increased to a maximum user-specified limit with several intermediate partial unloadings, which are conducted such that the indentation depth associated with plastic deformation can be determined. The applied indentation loads and associated penetration depths are measured during the test and used to calculate
the incremental true stress/true plastic strain values (flow curve) using elasticity and plasticity theories and semiempirical relationships that govern material behavior under multiaxial indentation loading. The analysis of the flow curve provides the mechanical properties and the fracture parameters for the material tested (Haggag et al. 1997).

The stress-strain microprobe can potentially be used to estimate Charpy energy and fracture toughness of ductile materials (Haggag et al. 1998, Byun et al. 1998). This particular use of the ABI technique is not apparent because indentation does not induce any cracking in the material. In addition, the stresses at the center of the contact surface of the test specimen under the indenter are compressive, whereas the stresses in the front of a crack tip in a fracture specimen are tensile. But elasticity theory and preliminary computer analyses results show that the stress triaxialities present at a crack tip in a fracture toughness specimen and at the center of the contact surface under the indenter may be similar. Therefore, the material at the center of the contact surface under the indenter experiences a degree of constraint similar to that experienced by the material at the crack tip, and the deformation energy at the center of impression may be comparable to that at the front of a crack tip.

It has been postulated from the above that the indentation energy per unit contact area up to an appropriate critical cleavage fracture stress or critical fracture strain relates to the fracture energy of a material. This energy is referred to as indentation energy to fracture (IEF). At low temperatures corresponding to the lower shelf and transition region, fracture in reactor pressure vessel steels occurs by a transgranular cleavage mechanism along low-energy cleavage planes. At higher temperatures corresponding to the upper shelf, fracture occurs by a mechanism of microvoid coalescence. Therefore, the concept of a critical cleavage fracture stress is applied to the lower shelf and transition region and is presented here. We are developing the application of critical fracture strain and will present the results at a later date.

The main advantages of the microprobe include (1) nondestructive, in situ measurements of mechanical properties of aged components, (2) measurements of local variations in mechanical properties, especially in the heat-affected zone (Miraglia 1997), (3) assessment of the effectiveness of reactor pressure vessel recovery after annealing, and (4) a small amount of material needed for testing. The potential advantages of the microprobe include (1) correlation with Charpy energy results, (2) determination of fracture toughness, and (3) a surveillance program based on broken Charpy specimens.

Additional experimental and analytical work is needed to realize this potential for estimating the fracture properties. In addition, currently the microprobe application is limited to unirradiated reactor pressure vessel materials and should be extended to irradiated reactor pressure vessel materials and thermally aged cast stainless steel materials (with the results validated).

**MAGNETIC TECHNIQUE**

Statically cast fittings, valve bodies, and pump bodies are employed in light water reactor (LWR) primary coolant systems. These components are subject to thermal aging at LWR operating
temperatures. Thermal aging causes an upward shift in the ductile-to-brittle transition temperature and a reduction in the fracture toughness, which challenges the structural integrity of primary pressure boundary components. The extent of thermal aging damage depends on the ferrite content of the material and its chemical composition. Ferrite measurements in statically cast components removed from power plants have revealed significant spatial variations of ferrite. The reason for such spatial variations is the complex shape of cast components and nonuniform cooldown during the casting process. As a result, similar spatial variations in thermal aging damage are also expected and an assessment based on nominal ferrite contents can be nonconservative. Therefore, there is a need for in situ determination of the transition temperature and fracture toughness of statically cast stainless steel components subject to thermal aging. Such measurements are likely to reduce uncertainties in current estimates of thermal aging damage in statically cast components and will help to focus in-service inspection efforts at locations in components experiencing the most damage.

Thermal aging alters the magnetic properties of cast stainless steel materials. The precipitated phases produced by thermal aging obstruct the rotation of magnetic domains. Changes in magnetic properties may be monitored by measuring the remnant magnetization of aged cast stainless steels (Evanson et al. 1992). Since remnant magnetization increases with ferrite content, exposure temperature, and time, it may be correlated with thermal aging damage. We are developing a correlation between remnant magnetization measurements and mechanical properties measured with the stress-strain microprobe. Maeda et al. (1996) has proposed a correlation for estimating room-temperature Charpy energy as a function of ferrite content and two electromagnetic properties (coercivity and resistivity). This correlation needs further validation.

POSTITRON ANNIHILATION MEASUREMENTS

Detecting early fatigue damage in the form of crystal defects or microscopic cracks will help identify the sites susceptible to fatigue cracking and optimize the in-service inspection program. The early fatigue damage is not detectable by conventional inspection techniques, which detect a crack only after it reaches a significant size, that is, a crack initiation stage. Advanced nondestructive inspection methods, however, can potentially characterize such damage; one such method is positron annihilation measurements.

Positron annihilation is a method that employs positrons from a radioactive source (²²Na, ⁶⁸Ge, or ⁵⁸Co) to detect the presence of changes in the materials' microstructure caused by irradiation, cyclic loads, or other stressors (Nishiwaki et al. 1979, Hautojarvi 1979, Gauster et al. 1978, Hughes 1980). Positrons from ⁵⁸Co generated in material during neutron irradiation can also be employed to detect microstructure changes. A positron is a charged particle equal in mass to an electron with a positive charge equal in magnitude to the negative charge of the electron. Upon injection into metal, positrons rapidly lose most of their kinetic energy by colliding with ions and free electrons. An energetic positron injected into a solid is slowed to thermal energies within about 10 ps (1 ps = 10⁻¹² s). Upon thermalization, the injected positron diffuses away from the point where it thermalized, until it finally annihilates with an electron. During this diffusion process, the positrons are repelled by positively charged nuclei and thus seek defects such as dislocations in the lattice sites, where the concentration of nuclei is smaller. A thermalized
positron has a typical mean velocity of $\sim 10^5$ m/s (Hughes 1980). The balance between the diffusion rate (after thermalization) and the annihilation rate of thermalized positrons is such that on average each positron has time to diffuse just a few tenths of a micrometer from its point of thermalization. Typical mean lifetime and total distance traveled by a thermalized positron before it annihilates with an electron are 200 ps and $\sim 20 \, \mu$m, respectively (Hughes 1980). The distance ($\sim 20 \, \mu$m) traveled after thermalization encompasses about $10^5$ lattice sites, so the positron will likely encounter a defect and be trapped, even if the defects are present at a small concentration (10 parts per million of defects ensure that on average there is one defect for every $10^5$ lattice sites) (Hughes 1980).

When a positron encounters an electron, it results in complete annihilation of both particles, and their mass is converted into pure energy in the form of two, or occasionally three, gamma rays. If the positron and the electron with which it annihilates are both at rest at the time of decay, the two gamma rays are emitted in opposite directions (180 degrees apart), in accordance with the principle of conservation of momentum. And, each annihilation gamma ray has an energy of 0.511 MeV, which is the rest energy of an electron and of a positron (Hautojarvi 1979, Allen et al. 1988). In fact, nearly all positrons are essentially at rest, but electrons are not. The momentum of an electron determines the momentum of the annihilating pair and causes the direction of the gamma rays to deviate from the nominal value of 180 degrees. Likewise, the energy of the annihilation gamma rays deviates slightly from 0.511 MeV, depending on the momentum of the electron, because of the Doppler effect.

Two characteristics of a positron and the radiation it emits upon annihilation with an electron make the positron annihilation method useful for detecting the presence and size of microscopic flaws in metals. First, the positive electrical charge of a positron causes it to be repelled by protons. This characteristic accounts for its attraction to dislocations, vacant lattice sites, vacancy clusters, cavities, and other open volumes (voids) in the metal, where the density of atomic nuclei is lower. Thus, a small increase in the number or size of the microscopic defects in a sample results in a large increase in the proportion of annihilation events occurring in the defects.

Second, annihilation radiation is sensitive to the momentum distribution of the electrons with which positrons annihilate. Defects contain a higher ratio of free (conduction) electrons to core electrons than perfect metal. This phenomenon can be explained by the tendency of free electrons to spill over into the defect more than core electrons. Core electrons have a higher linear momentum than do free electrons. Thus, gamma rays from annihilation events involving free electrons are more likely to approximate the energy (0.511 MeV) typical of gamma rays produced by events involving positrons and electrons at rest. These characteristics make it possible to detect the presence of defects from the energy spectrum of the gamma ray emissions.

Measurements of the gamma ray energy spectrum (Doppler broadened line-shape) can determine whether the positrons are interacting with free electrons at defects or core electrons in the bulk material. Less deviation from the nominal 0.511 MeV energy value, which implies that more gamma rays are detected in a given period of time at or very near 0.511 MeV and fewer detected
at other energy levels, indicates the presence of defects. This presence of defects can be correlated to a shape parameter, which quantifies the change in the shape of the energy spectra. The laboratory studies show that the shape parameter changes monotonically as fatigue damage increases.

**Development of Field Portable Positron Annihilation Measurement Technique:** Although positron annihilation measurements have been successfully used in a laboratory to measure the fatigue of typical nuclear power plant materials, the technique has not been commercialized: placing a positron source and a gamma ray detector inside a reactor pressure vessel or inside a primary coolant system piping near the inside surface where fatigue damage is generally higher is difficult. Also, positron annihilation gamma rays are potentially subject to interference from radioactivity in or on the component to be examined. Also, positrons from $^{22}\text{Na}$ or $^{68}\text{Ge}$ sources only penetrate, respectively, about 20 μm or 170 μm or less into steel, so this is primarily a near surface measurement technique. And, positron annihilation techniques can saturate at large defect concentrations.

The first problem (putting a source and a detector inside the reactor pressure vessel or primary coolant piping) was solved by noting that sufficient $^{58}\text{Co}$-produced positrons are present during refueling shutdowns. $^{58}\text{Co}$ is produced during normal operation of a nuclear power plant and is deposited on the primary coolant system surfaces and fixed in the approximately 0.1 micron corrosion layer. $^{58}\text{Co}$ is also embedded throughout the reactor pressure vessel wall adjacent to the reactor. A gamma-ray spectrum at a BWR plant was measured from the outside through about 2.5 cm of piping wall thickness during a refueling shutdown. The measurement indicates that the $^{58}\text{Co}$ positron annihilation peak at 0.511 MeV is measurable. So, we concluded that it is possible to make positron annihilation measurements of the fatigue damage at or near the inside surfaces of the primary coolant piping at nuclear power plants. Also, it appears that interference from other radioactivity in or on the primary coolant piping will not be a problem.

Positrons from $^{58}\text{Co}$ deposited on the insides surfaces of the primary coolant piping will only penetrate about 200 μm or less into the wall. However, microscopic fatigue cracks generally grow from persistent slip bands which intersect a surface. And, the experience in the nuclear industry to date indicates that the highest cyclic loads are on the inside of the coolant piping and that is where fatigue cracks have started. So, we will be measuring in the correct location if we use $^{58}\text{Co}$ positrons naturally available during refueling shutdowns.

The remaining issue, saturation of positron annihilation techniques can only be evaluated through additional experiments with appropriate fatigue samples. Therefore, we built fatigue specimens using typical nuclear grade material. The fatigue specimens were strain cycled with loadings representative of loadings expected in certain components (such as, the PWR surge and spray lines, and branch lines) during normal nuclear power plant operation. Specifically, the Type 304 stainless steel fatigue specimens were tested at room temperature under strain controlled conditions according to ASTM Standard E 606-92. The strain range was 0.66% (±0.33%) and the pseudo stress range was about 194 ksi. The specimens were tested at 17 cycles per minute using a
triangular waveform. Three specimens were tested to failure, which was determined to be an average of 39,800 cycles. The remaining specimens were tested to a predetermined fraction of the cycles to failure, namely 1, 5, 10, 20, 40, and 80 percent of the fatigue life (398 strain cycles were in each one percent of the fatigue life).

The fatigue specimens were coated with $^{58}$Co concentrations (nominally $2\mu$Ci/cm$^2$) similar to those found on piping in commercial nuclear power plants after 5 to 10 years of operation. The $^{58}$Co was electrodeposited on one side of the fatigue specimens to assure that the activity was evenly deposited. The side with the electrodeposited $^{58}$Co was exposed to air so that the positrons not injected into the fatigue specimen would annihilate at many centimeters from the detector. A plate with a thickness similar to nuclear power plant piping was placed between the fatigue specimen and the detector. This geometry is similar to the power plant situation except that the positrons released towards the inside of the power plant piping disperse and annihilate in water rather than air. The primary components of the detector system were a high-resolution, hyperpure germanium detector and a multichannel analyzer system.

Results of these tests show that the energy spectra are centered on about the 0.511 MeV energy level; and as the fatigue damage increases the spectra becomes narrower and its peak becomes higher. The reduction in the Doppler broadening because of fatigue damage is represented by the S parameter, which monotonically increases as the fatigue damage increases from 1% (398 cycles) to 100% of the fatigue cycles to failure. The results show that the gamma ray count does not get saturated at this strain range ($\pm 0.33\%$); earlier laboratory results support this conclusion (Gauster 1978).

Positron annihilation measurements on specimens subjected to different cyclic strain ranges and different temperatures need to be performed to further determine the applicability of this technique in the field. Future test plans include placing a plate with a thickness equal to nuclear power plant piping between the fatigue specimen and the detector to evaluate the loss of photon scattering. This geometry is similar to the power plant situation except that the positron released towards the inside of the power plant piping will disperse and annihilate in water rather than air. Therefore, these tests will be also assess the effects of water relative to air on the inside surface.

ULTRASONIC GUIDED WAVE TECHNIQUE

Ultrasonic guided waves propagating along a pipe or tube provides a global, economical inspection technique. This technique facilitates concurrent inspection of long length of piping (or tube) with removal of a narrow band of insulation at each end of the inspected pipe length. The guided waves can also be used to inspect inaccessible locations such as an embedded portion of the metal containment. This section summarizes the application of guided waves to inspect four different types of aging damage: (1) wall thinning of piping caused by flow-accelerated corrosion, (2) circumferential cracks in steam generator tubes caused by stress corrosion cracking, (3) corrosion damage to an embedded portion of the metal containment, and (4) thermal fatigue cracks in both base and weld
metals of piping. The first two applications have been developed and are being field tested. Development of the remaining two applications is being planned.

**Inspection of Piping Wall-Thinning:** A transmitter coil placed at one end of the pipe length being inspected produces a cylindrically guided ultrasonic wave that travels down the pipe to the receiving coil. Wall thinning encountered along the way obstructs energy flowing to the receiving coil. The guided waves are also partially reflected when they encounter welds and some of the energy is transmitted through the welds. These waves can travel through bends and elbows in piping if curvatures are not too large. Since cylindrically guided waves are multimodal in nature, more than one mode may be used. Some field demonstration show that such a use can identify defects in welds from defects in base metal.

Alleyne et al. (1995) used axially symmetrical, longitudinal Lamb waves, the L(0,2) mode, in the frequency range around 70 kHz. These waves are practically nondispersive and can travel tens of meters along the pipe, so a long length may be inspected from each transducer position. Tests performed at a chemical plant demonstrated that these waves can propagate distances over 50 meters in 75-mm and 150-mm diameter pipes, and defects about half the wall thickness deep and three times the wall thickness in diameter can be detected.

The Southwest Research Institute has developed an ultrasonic guided wave inspection technique for piping. The technique was applied to a laboratory mockup of part of 222-mm diameter, Schedule 120 (18.6 mm wall thickness) feedwater piping. The inspection results showed that the technique can detect an artificial flaw representing 3% wall loss over a distance of 36 m. Field application at a fossil steam plant showed that it was possible to transmit a signal over a distance of 13 m through insulated, feedwater piping; the piping diameter was 324 mm and thickness 34.5 mm (EPRI 1998).

**Inspection of Stress Corrosion Cracking in Steam Generator Tubes:** Rose et al. (1994) has developed a cylindrically guided ultrasonic wave technique to inspect steam generator tubing. In this application, the wave is launched down the length of the tube and travels several meters before attenuating. When the wave encounters a defect in the tube, a signal is reflected in the opposite direction and detected by the transmitting probe. Thus long sections of tubing can be examined completely and rapidly without a need for complicated and expensive tooling to insert and rotate the probe. The laboratory results show promise and indicate that circumferential cracking as small as 11% through the wall is detectable with this technique. But refinements are still needed to determine effective wave modes and optimize the technique so it is sensitive to certain types of defects, while being relatively insensitive to tube boundary conditions such as water or sludge loadings.

**Inspection of Corrosion Damage to Embedded Portions of Metal Containments:** Embedded portions of metal containments are susceptible to corrosion if exposed to groundwater. This can happen if the waterproof membranes under the basemats leak and the basemat concrete cracks. Reliable techniques for such inspections are not yet available. The electromagnetic acoustic transducer (EMAT) technique, developed earlier, has a low sensitivity to defects parallel to the containment surface and can detect corrosion defects only if larger than 75% of the wall thickness. An inspection technique based on using multimode guided plate waves (Lamb waves) in a through-
transmission mode may be more appropriate for this inspection. These waves can be produced with 76-mm diameter, piezoelectric transducers that require minimal access to the metallic surface. The plate-wave technique is more sensitive than the EMAT technique, which used shear waves. The EMAT technique is also sensitive to the stand-off distance between the transducer and the structure, and EMAT transducers tend to be large and expensive. In contrast, the plate-wave technique using the piezoelectric transducers is neither sensitive nor large and expensive.

Lamb waves, often called plate waves, exist in a plate-like structure and travel long distances, depending on the frequency and mode characteristics of the wave, and follow the contour of the structure in which they are propagating. Using plate waves is potentially a very attractive solution to the problem of inspecting embedded portions of LWR metal containments because they can be excited at one point on the structure, propagated over considerable distances, and received at a remote point on the structure. The received signal contains information about the integrity of the metal between the transmitting and receiving transducers. Nondispersive modes, which propagate long distances, have demonstrable sensitivity to wall thinning, cracks, and pits that may be present in the material being examined. The long range propagation and detection of the plate wave modes have been optimized and their interactions with defects have been reported (Pilarski et al. 1987, Alleyne and Cawley 1995). Measurements over 100 meters or longer distance have been demonstrated (Alleyne and Cawley 1992).

**Inspection of Thermal Fatigue Cracking in Piping:** Thermal fatigue has caused cracking in the base metal (away from the welds) of several PWR branch lines, such as safety injection lines. In at least four PWR plants, these cracks grew through the wall, leading to reactor coolant leakage. The base metal of the PWR surge and spray lines are also susceptible to thermal fatigue cracking. Although effective inspection techniques have been developed for detecting and sizing thermal fatigue cracks, volumetric inspection of the base metal is time consuming and expensive because large volumes of material are involved. Therefore, a global, cost-effective volumetric inspection technique is needed for detecting and locating thermal fatigue cracks in LWR piping weld and base metals. The cylindrically guided ultrasonic wave technique is one such inspection technique.

In the cylindrically guided wave technique, the waves, upon interaction with cracks, will emanate a set of first harmonic echoes (conventional ultrasonic reflected/mode-converted signals), which are received by both the transmitting and receiving transducers placed on the opposite sides of the cracks, and a second harmonic signal, which is received by the receiving transducer (Yost 1989, Morris 1983). Using all this information, an intelligent algorithm can be developed to detect and locate fatigue crack(s) that are partially or completely closed. Once located, currently available tip-diffraction techniques can be used for sizing these cracks. Thus, using guided waves will allow inspecting long pipe runs (5-300 feet) with a removal of only 6- to 8-in. of insulation at each end of the inspected pipe length.

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1 V. N. Shah, Private communication with Prof. Balasubramaniam, Mississippi State University, February 1998.
The ultrasonic wave modes can be generated using either a comb like transducer configuration (Rose et al. 1994) or circular ring type array transducers (Alleyne and Cawley 1995), which are attached to the outside surface of the pipe after removal of 6-8 in. of insulation at each location of guided wave generation. The length of travel of the guided waves will depend on the minimum size of the crack that has to be detected, and is estimated to be up to 300 feet. The smaller the crack size to be detected, the smaller the wavelength, which results in higher frequencies and consequently smaller travel distances because of ultrasound attenuation, which exponentially increases with frequency.

REFERENCES


