BNL-68166
Informal Report

NON-DESTRUCTIVE TESTING METHODS FOR GEOTHERMAL PIPING

M.L. Berndt
Energy Resources Division
Department of Energy Sciences and Technology
Brookhaven National Laboratory
Upton, New York, 11973

Prepared for:
Office of Wind and Geothermal Technologies
U.S. Department of Energy
1000 Independence Ave., S.W.
Washington, D.C. 20585

MARCH 2001

This work was performed under the auspices of the U.S. Department of Energy, Washington, D.C., under Contract No. DE-AC02-98CH10886.

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SUMMARY

Non-destructive testing is a key component of optimized plant inspection and maintenance programs. Risk based inspection, condition based maintenance and reliability centered maintenance systems all require detection, location and sizing of defects or flaws by non-destructive methods. Internal damage of geothermal piping by corrosion and erosion-corrosion is an ongoing problem requiring inspection and subsequent maintenance decisions to ensure safe and reliable performance. Conventional manual ultrasonic testing to determine remaining wall thickness has major limitations, particularly when damage is of a random and localized nature. Therefore, it is necessary to explore alternative non-destructive methods that offer potential benefits in terms of accurate quantification of size, shape and location of damage, probability of detection, ability to use on-line over long ranges, and economics. A review of non-destructive methods and their applicability to geothermal piping was performed. Based on this, ongoing research will concentrate on long range guided wave and dynamic methods.

TABLE OF CONTENTS

NON-DESTRUCTIVE TESTING METHODS FOR GEOTHERMAL PIPING

1.0 INTRODUCTION

Carbon and low alloy steel surface piping used in geothermal power plants is susceptible to internal damage caused by corrosion and erosion-corrosion. A survey of O&M-related materials needs in the geothermal industry indicated that there is a specific need for improved instrumentation and non-destructive testing (NDT) for monitoring internal damage (Allan, 1998). However, this issue is not being addressed in current research programs. NDT has been proven to be an essential tool for assessing corrosion- and erosion-related damage and an integral part of cost-effective maintenance programs in the chemical and petrochemical industries. Early detection of corrosion- and erosion-induced damage through routine NDT prevents unexpected failures and unscheduled maintenance. For maximum benefit NDT needs to be combined with issues of critical flaw size, fracture mechanics, probability of failure and acceptable level of risk.

It is essential that any NDT program takes into consideration the prevailing damage mechanisms, uses appropriate methods to detect the specific type of damage expected and targets the elements at risk. In the case of geothermal piping, damage of concern is corrosion caused by high temperature acidic and chloride-laden fluids and erosion-corrosion associated with flow, particularly for two phase fluids. Detection of pitting or other random localized types of corrosion is important as this is a common occurrence in geothermal environments. The selection of NDT methods for piping must also take into account practical considerations such as the presence of thermal insulation and scale, accessibility, operational temperatures, geometric parameters, and internal versus external inspection. The ability to detect corrosion under scaling or coatings would also be beneficial.

Ultrasonic NDT methods are typically used to measure wall thickness of piping and thereby detect loss of metal. Disadvantages of manual ultrasonic thickness tests are the point source nature of measurements, limited ability to detect early stages of damage, insulation removal requirement and high labor costs. Alternatives that can be used for on-line, long-range flaw detection with insulation intact are desirable. The objective of this project is to investigate alternative means of detecting corrosion- and erosion-induced damage in geothermal piping. Emphasis is being placed on dynamic response measurements and guided wave ultrasonic techniques. As part of the project, a survey was conducted to examine current and developmental NDT methods and their applicability to geothermal piping. The survey covers ultrasonic, electromagnetic, radiographic, thermographic and dynamic methods. The relationship between NDT, reliability centered maintenance and risk based inspection will also be addressed.

2.0 ULTRASONIC METHODS

Ultrasonic NDT methods employ waves with frequency greater than 2×10^5 Hz and a maximum typically around 10^6 to 10^7 Hz. The types of waves commonly used are bulk and guided. Bulk waves can be longitudinal or shear (transverse). Guided waves of interest include Rayleigh and Lamb. Ultrasonic testing involves generation and detection of ultrasonic waves with a transducer or pair of transducers. The transducer is typically coupled to the solid object of interest though a liquid, gel or viscous material. Piezoelectric materials are used in ultrasonic transducers. Several testing arrangements can be used. The first of these is the pulse echo (A-scan) technique in which a beam is transmitted into the material and reflects back from another surface. This technique uses a single transducer that acts as both the transmitter and receiver when the reflecting surface is parallel to the probe surface. The resultant oscilloscope trace shows the initial pulse and back echo. Flaws are indicated by the presence of an intermediate echo. Transmission techniques involve through-transmission testing with the transmitter and receiver on opposites sides of the specimen. Decrease in the amplitude of the signal occurs in the presence of flaws. Pitch-catch techniques use two transducers on the same surface of the material to be tested and angled transmission. Again, an intermediate echo between the initial pulse and back echo signifies a flaw. Other variations on these testing arrangements exist.

The results of ultrasonic testing can be displayed in several ways. A-scans show the received signal as a vertical deflection from the horizontal baseline that represents time or distance. Cross-sectional views of defects in a specimen are presented in B-scans. C-scans show a plan view of the tested surface. The flaw location and area are indicated. D scans are 2-D presentations of the time of flight values in a top view on the test surface. A P-scan is a projection of a B-scan to give a 3-D image.

2.1 Manual Ultrasonic Wall Thickness Testing

The simplest method of detecting metal loss in piping is to perform ultrasonic wall thickness measurements over points of the external surface. This method is based on travel time (time of flight) comparison of longitudinal waves. Thickness gauges are calibrated with standard blocks and then used to test the object of interest. The accuracy of commercially available gauges is typically ±0.5 to ±1.0% of the reading. The procedure is very labor intensive, requires removal of insulation or coatings and layout of a grid, and gives a limited point-by-point view of condition. Accessibility can also be a problem. With respect to geothermal piping, another consideration is the temperature limitation (< 50°C) of standard transducers used with ultrasonic thickness gauges. Therefore, high temperature transducers are required for testing operational systems. Transducers are available for use up to 500°C. Single position thickness measurements are most useful in cases where significant and uniform loss of metal due to corrosion or erosion has already occurred. The probability of detecting localized damage is a serious concern with manual ultrasonic thickness testing.

2.2 Automated and On-Line Ultrasonic Testing

Instrumentation exists to perform automated A-, B- and C-scans of wall thickness and provide digital, hard copy and video images. Numerous other improvements over manual testing are available. It is also possible to permanently install ultrasonic transducers for continuous monitoring in a particular location. On-line inspection (also called in-line inspection) can be achieved using intelligent pigs. Pigs are devices that are inserted into a pipeline and driven through by product flow. Intelligent pigs are instrumented to non-destructively survey the condition of the pipeline while it is in operation. Data is acquired and downloaded when the pig is retrieved to provide information on the nature and location of defects. Temperature, pressure and minimum bend radius limitations exist with intelligent pigs. On-line inspection with intelligent pigs is becoming an alternative to hydrostatic testing. These tools can use different NDT methods and the most common are ultrasonic and magnetic flux leakage (discussed later). Quantitative wall thickness measurements can be made around the entire circumference of the pipe and it is possible to distinguish external and internal metal loss. Corrosion detection thresholds for ultrasonic scanning pigs are typically greater than 20 mm diameter and greater than 1 mm depth. Crouch et al. (1996) compared the performance of intelligent pigs mounted with ultrasonic and magnetic flux leakage sensors in a 20 in. gas pipeline fitted with a test spool containing simulated defects. The ultrasonic method was found to be more accurate. In addition to ultrasonic tools for measuring wall thickness, intelligent pigs can be fitted with systems that use angular ultrasonic shear waves for detecting cracks. For inspection of geothermal piping it would first be necessary to remove any scale prior to using an intelligent pig and to select transducers with appropriate temperature range and ability to withstand corrosive environments.

2.3 Electromagnetic Acoustic Transducers

In order to overcome temperature limitations of conventional ultrasonic transducers, it is possible to use electromagnetic acoustic transducers (EMATs) to detect flaws and measure thickness. These produce ultrasonic acoustic waves by electromagnetic interaction with an electrical conductor and are used on the external surface of the object to be tested. The primary advantages of EMATs are that couplants are not required and that elevated temperatures can be withstood. Other advantages include tolerance of rough surfaces and ability to conduct high speed scans. Different wave mode EMATs are available (e.g., Rayleigh, Lamb, vertically polarized shear waves, horizontally polarized shear waves). EMATs are more versatile than conventional ultrasonic transducers using piezoelectric materials because of the additional wave modes that can be generated and received.

2.4 Long Range Guided Wave Testing

Another approach of interest for corrosion and erosion damage monitoring of geothermal piping is the use of long range guided (e.g., Lamb) waves. Lamb waves propagate between two parallel surfaces and can be used to detect changes in wall thickness. Advantages of using guided waves include ability to perform inspection over long distances, usefulness in inaccessible areas and lack of necessity to remove extensive amount of pipe insulation. Use of long range guided waves for piping inspection is reported by Alleyne and Cawley (1996, 1997), Pei et al. (1996), Rose et al. (1996), Lowe et al. (1998), Bray et al. (1998), Alleyne et al. (2000) and Wassink et al. (2000).

A guided wave system has been developed to test pipes 2 to 24 inches in diameter over a range of 50 m (Alleyne et al., 2000). Three or four rings of dry coupled piezoelectric transducers are clamped to the external pipe surface to excite low frequency longitudinal L (0,2) mode waves. It is also possible to use torsional waves. The system can detect corrosion defects causing 5-10% loss of cross sectional area at a particular axial location. Another system (Rose et al., 1996) uses a multi-element comb transducer. Generation of guided waves with different modes and frequencies by a comb transducer could be used to vary the sensitivity to different defect types and sizes. Both the ring and comb type transducer systems have been used to test insulated piping in the chemical processing industry.

Guided waves are not significantly affected by the presence of insulation. Liquid in the pipe and pipe coatings can affect the response. It is not known how the presence of internal corrosion products or scale would impact guided wave reflectivity and whether removal of such materials would be required prior to testing by this method. However, the advantages make long range guided wave testing worthy of more detailed investigation for geothermal applications. It would be particularly useful if the size of defects, in addition to location, could be indicated by this method. This issue is being explored by Rose et al. (2000) in terms of appropriate modes and frequencies and should also be analyzed for geothermal piping.

Ravenscroft et al. (1998) reported on a technique that uses creeping (lateral) and head waves for screening of piping and other geometries. Two transducers 1 m apart are used on the external surface to generate and receive waves. The presence of defects alters the signal magnitude and arrival time. Signal loss gives an indication of defect size. Full coverage inspection of the pipe is achieved. Both uniform corrosion and localized pitting can be detected.

3.0 ELECTROMAGNETIC METHODS

3.1 Eddy Current

In this review, electromagnetic NDT methods will include eddy current and magnetic flux leakage. Eddy current testing is a common method of locating corrosion- and erosion-induced damage in piping. The method uses a source of varying magnetic field such as a coil carrying alternating current with frequencies typically 10 Hz to 10MHz. This magnetic field induces eddy currents in the object being tested. The currents are influenced by physical properties of the material (e.g., electrical conductivity, magnetic permeability) as well as thickness and discontinuities (e.g., voids and cracks). Inspection conditions that affect eddy currents include frequency, coil size and shape, and separation between the coil and object (lift-off). Instrumentation is included in a testing system to detect changes in the magnetic field and compare the response with a reference.

A pulsed eddy current (PEC) tool can be used to test pipes for damage without the need for removal of insulation or coatings (Cohn and de Raad, 1998; Stalenhoef et al., 1998; Wassink et al., 2000). In this case, the test probe consists of a transmitter and receiver coil and instrumentation to send step current pulses to the transmitter coil. The pulsed magnetic field penetrates through insulation to induce eddy currents in the surface of the object under test. Diffusion of the eddy currents is dependent on material properties and wall thickness. Hence, by comparing the measured arrival time with that of calibration standards the wall thickness can be determined.

The PEC system can be used to measure wall thicknesses between 4 to 40 mm for pipe diameters greater than 76 mm and insulation thickness less than 100 mm (Cohn and de Raad, 1998). The upper temperature limit of the system is 500°C and wall thickness can be measured through external corrosion and scale. Aluminium and stainless steel lagging or cladding does not cause problems whereas galvanized lagging does. The wall thickness accuracy given by Cohn and de Raad (1998) with the pulsed eddy current system is better than ±0.5 mm with reproducibility of ±1 mm. Wassink et al. (2000) give a reproducibility value of 2% and a rate of measurement of 1000 per day under favourable conditions. The system gives an average thickness measurement over an area ("footprint") that depends the lagging material and standoff distance. Owing to the nature of the probe arrangement, the PEC method is more suited for detection of uniform corrosion or erosion rather than localized damage. Valves or other fittings within 150 mm of the probe can affect measurements.

Cohn and de Raad (1998) compared the results of wall thickness measurements performed on piping subjected to possible flow accelerated corrosion in fossil fuel power plants using ultrasonic and PEC methods. In general, it was found that there was good agreement between the test results when there was minimal wall thickness loss. Where the thickness loss was higher the difference between the two methods was greater, with the PEC method results indicating lower thickness than those measured by the ultrasonic method. This was possibly associated with the morphology of metal loss. Therefore, a suitable approach may be to use PEC tests for screening purposes and then perform more detailed ultrasonic tests in areas of concern (Wassink et al., 2000).

The ability of the PEC method to measure wall thickness through insulation or coatings and to withstand high temperatures makes it attractive for use in geothermal applications provided that the limitations are taken into account.

3.2 Magnetic Flux Leakage

Magnetic flux leakage (MFL) techniques for non-destructive testing of ferromagnetic materials use strong permanent magnets to magnetize the object of interest to near saturation flux density. Defects such as corrosion or erosion damage result in magnetic flux leakage. The flux leakage is detected by magnetic field sensors and is proportional to the volume of metal loss. The MFL technique does not require contact and can be automated for high speed testing. MFL is usually regarded as a qualitative technique, although some estimates of defect size can be made. Thus, MFL is largely a screening tool which can be followed by ultrasonic inspection for determination of defect size. Drury and Marino (2000) stated that the probability of detecting isolated pitting is greater with MFL than ultrasonics. In the case of pipelines or well casing, pigs mounted with a circumferential array of MFL detectors are used for on-line inspection. MFL pigs are available for a range of internal diameters, including small diameter heat exchanger tubes. An example of MFL inspection of piping is given by Stalenhoef et al. (1998). Elevated temperature testing requires electronics that withstand such temperatures. The accuracy of commercially available inspection tools is typically ±5 to 10% of wall thickness for general type corrosion and ±10 to 20% of wall thickness for pitting. Inspection of geothermal piping with MFL pigs would require removal of any scale or deposits.

4.0 RADIOGRAPHIC METHODS

Radiography uses X-rays or gamma rays to produce a two-dimensional image of an object. Flaws are indicated by changes in intensity in a radiograph. Wall thickness of insulated piping can be measured during service using radiographic techniques. It is also possible to examine scaling in pipes using radiography. Conventional tangential radiography requires skilled set up and interpretation. Advancements in digitization and image analysis of radiograms have improved this method. Furthermore, developments in technology now enable filmless, real-time imaging. These are discussed by Zscherpel et al. (2000) and Hecht et al. (2000). By combining imaging advancements and gamma ray detector technology with robotics, it is possible to perform real-time radiography and scan insulated or uninsulated piping for corrosion and erosion defects or loss of wall thickness (Gupta and Isaacson, 1997; Walker, 1998). The system uses a linear array of solid state detectors on one side of the piping and a low intensity Ir-192 gamma ray source on the opposite side. The detectors and source are mounted on a robotic crawler that travels at 2 to 4 ft per minute. Piping with diameters up to 30 in. have been successfully tested with this arrangement. Radiographic imaging of piping components such as tees, elbows and valves is possible with a filmless cassette system described by Gupta and Isaacson (2001). This is particularly important since such components are subject to flow accelerated corrosion and erosion. These radiographic techniques appear useful for geothermal applications.

5.0 THERMOGRAPHIC METHODS

Thermographic testing involves subjecting the object of interest to heating or cooling and measuring the resultant temperatures or thermal gradients with heat sensors. The presence of flaws alters the thermal properties and consequent heat transfer behaviour. Thermograms are produced and flaws are indicated by changes in temperature contrasts as a result of modifications in heat flow. This is a non-contact method that has broad application in NDT. Maldague (1999) describes the use of pulsed active infrared thermography (PAIRT) for inspection of uninsulated piping. This technique involves transient thermal perturbation of the object. The resultant sequence of temperature distribution is monitored with an infrared camera and the data is recorded digitally. PAIRT can be used either internally or externally. Two versions are considered. The first of these is transmission in which a thermal transient is generated inside the pipe by changing the temperature of the circulating fluid and the temperature distribution on the external surface is determined with an IR camera. Wall thickness can then be calculated by the simple relationship between the time of observation when thermal contrasts appear, thickness and thermal diffusivity. The second version is by reflection in which a uniform heat source is applied to the exterior of the pipe and the resultant temperature distribution on the external surface is again observed using an IR camera. The transmission method reportedly gives better thermal contrasts. Thermography in geothermal applications would be limited to uninsulated piping.

6.0 DYNAMIC METHODS

Dynamic NDT involves application of a known vibration to an object or structure and observation of its vibrational response. The dynamic response is sensitive to the presence of flaws. It is also possible to use dynamic methods to determine variations in material properties. Two different methods are used in dynamic testing: (a) measurement of natural (resonant) frequency and (b) measurement of rate of attenuation.

Objects or structures can vibrate at different natural frequencies. These frequencies are a function of geometric parameters, physical constants (e.g., elastic modulus, density, Poisson's ratio) and end constraints. Modes of vibration include flexural, torsional, longitudinal, radial, diametrical and annular. Modal analysis refers to study of the natural frequencies, damping values and mode shapes of physical systems. Measurement of natural or resonant frequency involves application of a vibration force and the frequency at which natural frequency is matched is determined. Ambient vibration and the resultant response is another alternative. Resonant frequency tests require that the object be supported at the nodes for the mode of vibration under consideration. The vibration force is applied by a piezoelectric transducer, electromagnetic vibrator or other means of inducing vibration. The vibration is detected by some form of pickup. A range of physical properties can then be calculated based on the measured resonant frequency. Elastic properties, and resultant resonant frequencies, are affected by flaws.

Use of resonant frequency techniques to detect flaws or damage in structures requires some form of comparing the response of the test structure to one that is known to be sound and using this information to ascertain the nature and location of damage. This is where modal analysis becomes applicable in both theoretical and experimental forms. The deviations in measured global vibrational response of the structure must be correlated with localized damage. In order to achieve this, it is necessary to consider the local response parameters such as mode shape data. Although resonant frequency and modal analysis techniques have been applied to assess the integrity of structures such as bridges, the approach is not as mature as other NDT methods. Modal analysis testing for NDT is an active field of research.

The other form dynamic NDT is measurement of attenuation, or damping, rate. In this method an object is induced to vibrate in one of its natural frequency modes by a vibration pulse. The pulse is then stopped and the subsequent decay in vibration is measured. The specific damping capacity is then determined from the decay curve. Since the damping capacity is increased by the presence of flaws, this method can be used for NDT of objects.

Kriel and Heyns (1999) have investigated the applicability of dynamic methods in non-destructive damage detection for insulated piping. In this particular case, ambient excitation due to flow was considered. The study examined the important structural modes through finite element analysis and verified these experimentally through frequency domain and time domain modal parameter estimation. The dynamic response to different forms of damage was investigated. It was determined that flow-induced vibration was sufficient to excite modes of interest and that the mode shapes were sensitive to uniform damage rather than localized corrosion. Temperature did not affect the results. The dynamic method of NDT appears to have potential for use in geothermal piping. Further study is necessary to consider the ability to detect localized corrosion, minimum size of defect that can be detected, range of application and possibility of using forced vibration. It is also important to determine the influence of adherent scale on dynamic response and whether scale removal is necessary.

7.0 OTHER METHODS

Some other NDT methods for inspecting piping are considered in this survey. The first of these is the use of borescopes with associated video cameras. High resolution video images of damage can be achieved. In the case of geothermal piping, viewing of corrosion- and erosion-induced damage will first require removal of scale or other deposits. Visual inspection can provide a useful supplement to more quantitative measurements of metal loss.

Stark (U.S. Patent No. 5963030, 1998) has patented an electromagnetic pipe inspection system. The system consists of a low frequency electromagnetic source and detector in a ring assembly that is used for external inspection without the need for removal of insulation. The ring assembly travels along the pipe coaxially centered. The electromagnetic source in the ring assembly induces a secondary signal or current in the piping which is then detected and correlated to pipe thickness. Further details are available in the patent. This system is worthy of further investigation for applicability in geothermal power plants.

Magnetostrictive sensors have been studied for NDT of thermally insulated piping by Kwun and Holt (1995). A system has been patented by Kwun and Teller (U.S. Patent No. 5581037, 1995). These sensors generate and detect mechanical waves in ferromagnetic materials. NDT of a pipe using the magnetostrictive sensor technique uses two sets of an inductive coil encircling the pipe and a bias magnet. A time-varying magnetic field is applied to the pipe by the transmitting coil and this generates an elastic wave in the pipe due to the magnetostrictive effect. The waves propagate along the pipe in both directions. The receiving magnetostrictive sensor uses the other encircling coil to detect changes in magnetic induction in the pipe due to the inverse-magnetostrictive effect when the waves pass through. The system does not require a couplant or direct contact and can be used further away from the object under inspection than EMATs. It is claimed that the magnetostrictive sensor technique can be used to detect internal or external wall thinning in a pipe over long (100 m) distances from a single sensor. The technique can be used at elevated temperatures provided they are lower than the Curie temperature of the pipe material. Kwun and Holt (1995) suggested further studies to determine minimum detectable defect size and effects of various factors on wave propagation. Development of field inspection equipment was also proposed.

8.0 ROLE OF NDT IN RELIABILITY CENTERED MAINTENANCE AND RISK BASED INSPECTION

NDT is an integral component of reliability centered maintenance (RCM) and risk based inspection (RBI) programs to manage physical assets. RBI considers the probability and consequences of failure and prioritizes inspection needs based upon risk. As an example, elbows in piping are at greater risk of erosion-corrosion and would be prioritized higher than straight piping. RBI is aimed at optimizing the effectiveness of inspection and overcoming deficiencies of a fixed interval approach. Quantitative RBI incorporates NDT to monitor condition of a system. Condition based maintenance can then be implemented. The use of a condition based approach to maintenance can result in reduction of unnecessary preventative maintenance in addition to justified and cost-effective maintenance actions.

The use of RCM in geothermal power plants is discussed by Grande et al. (2000). RCM is a process used to determine what must be done to ensure that a system continues to operate as required. Seven basic questions are asked in RCM that relate to functions and performance standards, functional failures, causes, effects and consequences of failure, proactive tasks to predict and prevent failure, and default actions if proactive tasks cannot be found. Detection of corrosion- and erosion-related damage through NDT is necessary for prediction and prevention of failures.

Translation of the results from NDT to remaining service life prediction is another area requiring development for successful implementation of quantitative RBI and RCM in geothermal power plants. This may require consideration of failure mechanisms, kinetic and probabilistic aspects of corrosion and erosion, mechanical and thermal stresses, and structural analysis of damaged systems. Information on the geometry of the flaw in addition to its size is vital for fracture mechanics-based analysis and prediction of remaining life. Thus, the selected NDT method should be able to identify flaw geometry. An example of combining NDT with probabilistic failure analysis for oil and gas pipelines is given by Pandey (1998). It is also necessary to define repair/replace criteria as part of a preventative maintenance program.

Integration of NDT with on-line monitoring of corrosion activity provides additional information on component performance. Inman et al. (1998) describe a rig designed for on-line corrosion monitoring of carbon steel exposed to flow and chemical conditions simulating those encountered in geothermal steam pipelines. Different monitoring techniques were applied. These included weight loss coupons, electrical resistance, linear polarization resistance, corrosion potential measurements, hydrogen probe and thin layer activation. Estimation of corrosion rate from these techniques can be used as part of remaining service life calculations.

9.0 CONCLUDING REMARKS

The NDT methods described each have certain advantages and disadvantages. The ideal method for geothermal piping would accurately detect the size and location of all corrosion- and erosion-induced damage on-line without the need for removal of insulation, coatings or scale, be non-intrusive, provide real time digital information, and be rapid and cost-effective. It is common practice in many industries to combine two or more different NDT methods in a thorough evaluation of any component. For example, one method could be used to delineate areas of damage and then followed by another to give more quantitative and detailed inspection of the identified areas.

Borescopic inspection offers a visual assessment of the internal condition of piping. Manual ultrasonic wall thickness testing has distinct limitations when used as the sole NDT method. However, it may be useful for detailed inspection of an area found by a screening method to be damaged. On-line internal ultrasonic inspection with intelligent pigs offers many advantages over manual testing. For geothermal piping the presence of scale and maximum operational temperatures of the transducers needs to be considered. Electromagnetic acoustic transducers are more flexible than conventional ultrasonic transducers in that couplants are not necessary, higher operating temperatures can be tolerated and different wave modes can be generated. Long range guided ultrasonic wave testing is of great potential for use in external inspection of insulated geothermal piping. Further study of any influence of scale and the detectable defect size is required to ensure the usefulness of this technique.

Electromagnetic techniques that include eddy current and magnetic flux leakage are of interest. Pulsed eddy current testing can be used on insulated piping at elevated temperatures. However, it is more suited to detection of uniform damage and may be best used in conjunction with another technique, such as ultrasonic inspection. Magnetic flux leakage sensors can be used with intelligent pigs to rapidly screen piping for damage. This technique is somewhat qualitative. Automated radiographic inspection is another viable NDT method for geothermal piping. Thermographic methods may be useful for detecting damage in uninsulated piping. Dynamic methods have promise for geothermal applications owing to the ability to perform on-line long range testing in the presence of insulation and elevated temperatures. More research is necessary to determine defect detection limits of this approach. Other techniques, such as magnetostrictive sensors, may play a role in the future.

Ongoing research at BNL will focus on ultrasonic guided wave and dynamic methods for detection of corrosion- and erosion-induced damage in geothermal piping. Theoretical aspects along with experimental and field verification will be undertaken. It is also intended to integrate improved NDT methods with piping integrity assessment, remaining life prediction and implementation of RCM and RBI programs.

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12.0 ADDITIONAL NDT RESOURCES

American Society for Nondestructive Testing (www.asnt.org)

British Institute of Non-Destructive Testing (www.bindt.org)

Canadian Society of Nondestructive Testing (www.csndt.org)

European Federation for Nondestructive Testing (www.efndt.org)

International Committee for Non-Destructive Testing (www.aipnd.it/icndt.htm)

International Foundation for the Advancement of Nondestructive Testing (www.ifant.org)

Nondestructive Management Association (www.ndtma.org)

e-Journal of Nondestructive Testing and Ultrasonics (www.NDT.net)

Recent listings of NDT equipment manufacturers and suppliers and NDT service companies are given in Buyers Guides published by NACE (Materials Performance, Volume 39, Number 11, November 2000) and ASM International (Advanced Materials and Processes, Volume 158, Number 5, November 2000).