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Extended In-Situ and Real-Time Monitoring
Task 1: Monitoring Real Time Materials Degradation

Nuclear Engineering Division

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Task 1: Monitoring Real Time Materials Degradation

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for:

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U. S. Nuclear Regulatory Commission

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EXECUTIVE SUMMARY

The overall objective of this project was to perform a scoping study to identify, in concert with the nuclear industry, those sensors and techniques that have the most promising commercial viability and fill a critical inspection or monitoring need. Candidates to be considered include sensors to monitor real-time material degradation, characterize residual stress, monitor and inspect component fabrication, assess radionuclide and associated chemical species concentrations in ground water and soil, characterize fuel properties, and monitor severe accident conditions. Under Task 1—*Monitoring Real-Time Materials Degradation*—scoping studies were conducted to assess the feasibility of potential inspection and monitoring technologies (i.e., a combination of sensors, advanced signal processing techniques, and data analysis methods) that could be utilized in LWR and/or advanced reactor applications for continuous monitoring of degradation in-situ. The goal was to identify those techniques that appear to be the most promising, i.e., those that are closest to being both technically and commercially viable and that the nuclear industry is most likely to pursue. Current limitations and associated issues that must be overcome before commercial application of certain techniques have also been addressed.

A review of the available literature was carried out with the goal of identifying the emerging trends and potential technology gaps in sensors and techniques in application to in-situ inspection and monitoring of material degradation in nuclear power plant structures, systems, and components (SSCs). The focus of this scoping study was mainly on promising technologies for early detection and characterization of degradation in susceptible materials and components. To help narrow down the scope of studies on this rather broad topic, the review was limited mostly to the emerging technologies for detection of damage and degradation in passive components, which inherently pose a greater challenge to nondestructive examination (NDE) and on-line monitoring (OLM) methods—also referred to as structural health monitoring (SHM) in other industries. To that end, emerging inspection and monitoring techniques for plant life extension were reviewed. To a lesser extent, advanced technologies for specialized and new applications were also studies. Little emphasis was placed on sensor systems for OLM of basic process parameters and active components (i.e., temperature, pressure, level, flow, vibration, leak, valve position, radiation/flux, coolant chemistry, etc.).

A number of emerging NDE techniques that could potentially provide more efficient and reliable inspection and monitoring capabilities have been identified. A non-exhaustive review of the available literature was made on the application of these technologies particularly with regard to corrosion, corrosion-cracking, fatigue, creep, metallic diffusion, and in susceptible materials and components such as similar/dissimilar metal welds, vessel claddings, and concrete. Some promising active and passive sensing technologies that could potentially allow in-situ monitoring of crack initiation and growth have also been noted. Literature review was also conducted of the existing and emerging inspection and monitoring techniques in application to some specific areas of interest to this scoping study. The SSCs of particular interest included buried components and concrete structures in NPPs. A number of promising NDE techniques for inspection of buried piping that require either excavation or entry methods (e.g., VT, GW-UT, PEC) and those deployed using pigs (PEC, RFECT, MFL, UT, and laser-UT) were noted. For inspection of concrete structures, in view of their application, both common NDE techniques (e.g., rebound hammer, penetration resistance, AE, VT, RT, GPR, photography, half-cell potential) and emerging (e.g., enhanced VT, IR thermography, SASW, NMR, RT, UT) was noted. Additionally, a review was conducted of the existing and emerging technologies for detection of leaks in reactor coolant pressure boundary (RCPB). Some general suggestions were made in connection with improving the reliability of existing leak detection techniques. The current state-of-the art with regard to measurement of residual stress (RS) in components was also reviewed. Both conventional and promising emerging techniques (compact XRD, laser shearography, and UT method based on L_{CR} waves) were discussed.

More prominent emerging NDE technologies, in their various forms, that can be employed for in-situ inspection of NPP components include enhanced ECT, UT, VT, and RT methods. Eddy current testing with high resolution arrays of thin-film and solid-state elements are being evaluated for a number of inspection and monitoring applications. For examination of electrically thick components, in addition to conventional remote field and pulsed ECT methods, specialized deep-penetrating probes with inductive and magneto-resistive elements have the potential to provide improved detection sensitivity in comparison to conventional eddy current techniques. For detecting deeply embedded flaws, the emerging SQUID technology can provide superior sensitivity to conventional induction sensing techniques. Magneto-optic imaging systems also hold promise for real-time visualization of eddy current distribution over relatively large areas.

A number of versatile UT techniques have been developed in recent years. Modern UT instruments employing phased array technology are evolving rapidly and are expected to be more widely deployed in the future for field applications. Newly developed UT methods based on TOFD, long-range guided waves, laser excitation and detection, nonlinear ultrasonics, and EMAT technology are being evaluated for a wide range of NDE applications including for inspection of SSCs in nuclear power plants. Both laser UT and EMAT are non-contact techniques (i.e., eliminate the need for couplants used in conventional UT) that inherently allows for more rapid examinations. The non-contact nature of these methods is of particular significance as it overcomes a major limitation of traditional UT with piezoelectric transducers. These methods further allow measurements to be made under adverse test conditions (e.g., parts at elevated temperatures and in corrosive environments) for which the use of contact type probes may be impractical. Assessments to date suggest that phased array EMAT technology could offer certain advantages over conventional UT for examining coarse grain materials (e.g., cast stainless steel components) and for inspection of SSCs with non-ideal surface conditions including parts with coating and cladding. Further confirmatory studies, however, are needed to reliably demonstrate the performance of emerging UT techniques for routine field use.

Several other emerging and newly developed NDE methods with potential application to in-situ inspection and monitoring of SSCs in nuclear power plants have also been noted in this report. They include enhanced VT systems with miniature video cameras and advanced image processing and visualization tools, optical methods based on fiber optic sensors and digital speckle correlation technique, radiographic and diffraction methods with portable X-ray instruments, IR thermal imaging including vibrothermography and thermal tomography, and RF and microwave techniques. Some of the aforementioned technologies are expected to play a more prominent role for NDE of advanced reactor systems that employ ceramic and composite materials for high temperature applications. Promising in-situ NDE methods using active and passive distributed sensor elements (capacitive, inductive, fiber optic, acoustic, and strain gauges) have also been noted in this report. Significant level of research and development is currently being carried out in this area. A wide suite of sensors and techniques have been developed for applications in automotive, aerospace, and construction industries. Applicability of the emerging sensor systems to the inspection and monitoring of NPP components remains to be demonstrated.

In general, common features of modern NDE equipment include: Higher degree of inspection automation (hardware and software); faster inspections through employment of linear and matrix array sensor configurations; increased accuracy and quantification capability; greater penetration depth and higher spatial resolution; more flexible and modular tools allowing incorporation of multiple sensors in the probe assembly; compact systems (integrated inspection units for rapid deployment); rugged probes for operation in harsh environments (elevated temperature and pressure, radiation, moisture, and corrosive media); inspection techniques that are less affected by the surface condition of components.

Traditional analog systems for sensing basic process parameters in NPP operation have limitations with respect to accuracy, ease of maintenance and data quality. To reduce the costs and improve performance of NPPs digital systems are being applied as replacements in the nuclear industry. A wide range of sensors are currently available for measuring basic process parameters and for monitoring of degradation in active components and plant instrumentation. In addition to conventional sensors (e.g., thermocouples, resistance temperature detectors, differential pressure sensors, etc.) a number of new industrial grade sensors (e.g., fiber optic, ultrasonic, resistive, capacitive, inductive, etc.) are now commercially available. Review of the open literature generally suggests that there are currently no major technology gaps with regard to sensors for measuring basic process parameters and for monitoring of active components. Efforts, however, are needed toward development of procedures for adapting and ultimately deploying the existing sensors and prototypes devices for NPP applications. This process will inherently require involvement by utilities, professional committees (IEEE, ISA, ASTM, etc.) as well as the regulatory organizations.

Existing OLM systems operate primarily as fault-detection systems. They are used to monitor instrument channel performance and as sensor validation tools. A number of projects are currently being sponsored by utilities and federal agencies to develop advanced OLM systems for diagnostics and prognostics that not only detect but also forecast the health of operating machinery. While significant progress has been made in that area, advanced OLM systems have not yet been widely deployed for use in the existing fleet of reactors. This trend seems to be changing as the technology becomes more mature and proper performance demonstration and qualification procedures are put in place. It is worth noting that while the emerging OLM systems that utilize the available information from the existing plant sensors are expected to improve the reliability in monitoring of active components, health monitoring of passive components remains to be a challenge in the foreseeable future. New sensor technologies and specialized in situ NDE techniques thus need to be developed in parallel in order to take full advantage of the cost benefit potential of modern OLM systems.

A number of recent publications were referenced in this report in connection with advances in I&C technology for selected applications to NPP upgrades and in new plants. The emerging trends in sensors and measurement systems as well as surveillance, diagnostics, and prognostics methods were discussed. In general, the principal variables measured for safety-related applications continue to be neutron flux, temperature, pressure, radiation, flow, position, and level. Many of these sensor technologies, although developed many years ago, have not been widely deployed in the nuclear power plants in the U.S. As noted earlier, promising OLM technologies identified in a number of recent reports on I&C technology are applicable primarily to monitoring of active plant components.

For long term predictive maintenance in NPPs trending (fault diagnosis) based either on empirical or physical models has the potential to more accurately predict the remaining useful life of components in comparison to conventional fault detection methods. Applicable condition monitoring techniques include those that employ microphones and accelerometer type sensors for vibration monitoring and for acoustic monitoring in its various forms (crack initiation and growth monitoring, acoustic leak detection, vibration monitoring, loose part monitoring, etc.). Other condition monitoring techniques include reactor noise analysis and motor electrical signature analysis. Hybrid condition monitoring technique (integration of two or more condition monitoring methods that combine physical and empirical modeling) is noted as the potential future trend in OLM technique for the nuclear power industry. The reliability of emerging OLM technologies for early detection of material degradation in passive components and prediction of their remaining useful life needs to be further evaluated.

A number of publications and reports have also been reviewed in connection with possible in-situ detection and monitoring of SCC initiation and growth in LWRs based on coolant chemistry. The reports provide an overview the state-of-the-art with regard to OLM of water chemistry and corrosion in operating reactors and on the development and qualification of promising monitoring techniques. In-situ high temperature measurements can potentially overcome known disadvantages associated with conventional sampling procedures. The results of laboratory and field experiments on the application of ECP, ECN, EN, and EPN were discussed. In general, high-temperature OLM is needed primarily for secondary side measurements in PWRs. Despite their long history the techniques used for monitoring of SCC have not attained widespread use. Also, it is not yet clear whether direct measurement of corrosion phenomena (corrosion rate, oxide-film characteristics, cracking susceptibility, etc.) will lead to plant implementation. Monitoring the behavior of SCC in pressure-retaining and reactor-internal components in BWRs has been studied extensively. No method is currently available for OLM of crack initiation through SCC. Various methods for in-situ determination of the tendency for crack growth have been used in commercial reactors both in recirculation piping and side-stream autoclaves and in-core to monitor IASCC. Such crack-growth monitors are able to provide valuable real-time information. Optical methods and advanced electrochemical techniques (thin-film, contact electrical resistance, EN, etc.) are proving very useful for mechanistic studies. Further development of these sensor technologies, however, is required before they can be considered for field use. In-core crack-growth-rate measurements are in use for IASCC studies at various test reactors and have also been performed in commercial plants, but they cannot yet be regarded as a routine monitoring tool. In-situ monitoring can provide new and valuable information to plant operators, however, full benefit from using OLM sensors will only be obtained if the data can be processed in real time using computer-aided diagnosis systems.

Limited scoping studies were also conducted on emerging technologies for on-line SHM and condition based damage state forecasting. Adaptation of real-time or online structural health monitoring using passive and active distributed sensors is expected to play an increasingly greater role in the nuclear power industry. Analogous to the passive sensing approach such as AE, active sensing can be employed for online estimation of damage states. Nonlinear pattern reorganization techniques can be used to forecast the future damage states based on the current estimated states. The results of studies to date suggest that nonlinear pattern recognition in conjunction with machine learning algorithms could provide the means to identify complex fault trends and to further help forecast potential events at an earlier stage. Integrated sensing systems are being developed and marketed for monitoring a wide range of physical and process parameters. Adaptation of smart sensor networks to SHM in the nuclear power industry is an active area of multidisciplinary research and development. Extensive performance demonstrations must be conducted and new codes and regulatory guidelines need to be developed before any such new technology gains widespread acceptability for monitoring of SSCs in the nuclear power industry.

A limited scoping study was also performed on advanced sensor technologies. A review was provided of “smart” and “intelligent” sensor technologies with potential application to monitoring of material degradation in NPPs. Smart and intelligent sensors in the future are expected to monitor both internal and external stressors and to further provide self-diagnostics capability. Energy-efficient sensors based on MEMS with embedded artificial intelligence capability are being developed. Application of these advanced sensor technologies to monitoring of SSCs in nuclear plants will be the topic of future research activities. A large body of literature also exits on the topic of WSNs based on smart sensor technology. Majority of research activities in this area are associated with the wireless networking and data interpretation aspects of such systems with less emphasis placed on the sensor technology. A more detailed review of WSN technology is provided in connection with Task 2 scoping studies conducted under this program.

Acronyms and Abbreviations

ANL	Argonne National Laboratory
ACI	American Concrete Institute
ACPD	AC potential drop technique
AE	Acoustic emission
AMR	Anisotropic magnetoresitive
ASTM	American Society for Testing and Materials
BWR	Boiling water reactor
CCD	charge-coupled device
CT	Computer tomography
DCPD	DC potential drop technique
DCVG	direct current voltage gradient
DOE	(United States) Department of Energy
DSCT	Digital speckle correlation technique
ECA	Equipment condition assessment
ECN	Electric current noise
ECP	Electrochemical corrosion potential
ECT	Eddy current testing
EMAT	Electromagnetic Acoustic Transducer
EN	Electrochemical noise
EPRI	Electric Power Research Institute
ER	Electrical resistance
FWM	Fleetwide monitoring
GMR	Giant magnetoresitive
GPR	Ground penetrating radar
GW-UT	Guided-wave UT
IAEA	International Atomic Energy Agency
IASCC	Irradiation assisted stress corrosion cracking
I&C	Instrumentation and controls
IEEE	Institute of Electrical and Electronics Engineers
IR	Infrared
ISI	Inservice inspection
JNT	Johnson noise thermometry
LUT	Laser UT
LWR	Light water reactor
MEMS	Microelectromechanical Systems
MFL	Magnetic flux leakage
MHI	Mitsubishi Heavy Industries
MOI	Magneto-optic imager
MPT	Magnetic particle testing
MR	Magnetoresistive
MW	Microwave

NDE	Nondestructive examination
NDI	Nondestructive inspection
NDT	Nondestructive TESTING
NEI	Nuclear Energy Institute
NMR	Nuclear magnetic resonance
NN	Neural network
NPP	Nuclear power plant
NRC	(United States) Nuclear Regulatory Commission
OLM	On-line monitoring
PNNL	Pacific Northwest National Laboratory
POD	Probability of detection
PA-UT	Phased array UT
PEC	Pulsed eddy current
PT	Liquid penetrant testing
PWR	Pressurized water reactor
RCPB	Reactor coolant pressure boundary
RF	Radio frequency
RG	Regulatory Guide
RS	Residual stress
RT	Radiographic testing
RFECT	Remote-field eddy current testing
SASW	Spectral analysis of surface waves
SCC	Stress corrosion crack/cracking
SHM	Structural health monitoring
S/N	Signal-to-noise ratio
SSCs	Structures, systems, and components
SQUID	Superconducting quantum interference device
TOFD	Time-of-flight diffraction
U.S.	United States
UT	Ultrasonic Testing
VT	Visual testing
WSN	Wireless sensor network
XRD	X-ray diffraction

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1. Objective

The overall objective of this project was to perform a scoping study to identify, in concert with the nuclear industry, those sensors and techniques that have the most promising commercial viability and fill a critical inspection or monitoring need. Candidates to be considered include sensors to monitor real-time material degradation, characterize residual stress, monitor and inspect component fabrication, assess radionuclide and associated chemical species concentrations in ground water and soil, characterize fuel properties, and monitor severe accident conditions.

This scoping study encompassed four primary areas and will inform NRC regulators of the monitoring and inspection requirements and available capabilities to monitor:

(1) Real-time materials degradation,

(2) Severe accident conditions,

(3) Performance of long-term dry cask storage systems, and

(4) Compliance with 10CFR Part 20.1406 involving early detection of abnormal radioactive releases.

This work evaluated the feasibility of existing commercial monitoring sensors and techniques to identify possible safety and regulatory issues. A follow-on research plan (or plans) may be developed to assess these issues for a few of the most promising sensors or techniques.

Task 1—*Monitoring Real-Time Materials Degradation*—This limited study was aimed at evaluating the feasibility of potential inspection and monitoring technologies (i.e., a combination of sensors, advanced signal processing techniques, and data analysis methods) that could be utilized in LWR and/or advanced reactor applications for continuous monitoring of degradation in-situ. The goal was to identify those techniques that appear to be the most promising, i.e., those that are closest to being both technically and commercially viable and that the nuclear industry is most likely to pursue. Current limitations and associated issues that must be overcome before commercial application of each technique were evaluated. The studies are to help with assessing the likelihood that these limitations and issues can be overcome. References are also made to current research (i.e., that sponsored by academia, the nuclear industry, other industries, and other government agencies) that might address these limitations. Some general comments are also provided about the safety and regulatory issues associated with each technique. The results of this evaluation could be used as the technical basis for assessing the adequacy of future industry use of these techniques and to determine if follow-on confirmatory research is appropriate. If so, a research plan could be developed to address the safety and regulatory issues associated with the most promising techniques.

Advanced reactor designs present several unique considerations related to inservice inspection (ISI). Proposed designs envision longer times between scheduled outages and operation at higher temperatures than those in conventional LWRs. Longer outage intervals may require more sensitive nondestructive examination/inspection (NDE/NDI) methods to improve ISI reliability and accuracy. One possible approach is the use of techniques with increased sensitivity and spatial resolution. An alternative or supporting strategy may be to use in-situ and continuous monitoring methods to assess degradation more frequently than the outage interval. Advanced signal processing and data analysis methods are also expected to play an important role in the development of NDE tools for advanced reactors. Earlier NRC-sponsored work should be reviewed to provide background and technical guidance and to explore implementation issues related to the use of on-line monitoring (OLM) – also referred to as structural health monitoring (SHM) in other industries – for the extension of safety critical sensor calibration intervals.

2. Scope of Study

Activities under Task 1 were associated with the review of literature on existing and emerging sensors and nondestructive evaluation (NDE) techniques in application to in-situ monitoring of material degradation. A large body of literature exists on the broad subject of sensors and instrumentation for monitoring of active components and basic process parameters at nuclear power plants (NPPs). The goal of this study, however, was to identify promising techniques that could either provide improved capability over existing methods or fill the potential technology gaps in early detection of degradation in susceptible materials and components. To further help narrow down the scope of studies on this rather broad topic, the review of literature was focused mostly on the inspection and monitoring technologies for detection of damage and degradation in passive components. To that end, sensor and NDE technology needs were divided into three broad areas of application:

1) On-line monitoring of process parameters,

2) Inspection and monitoring for plant life extension, and

3) Advanced technologies for specialized and new applications.

The scoping studies under Task 1 revolved mostly around the second and the third area of application and with a lower level of consideration for the first area of application listed above. Sensor systems for on-line monitoring (OLM) of process parameters include those for measuring temperature, pressure, level, flow, vibration, leak, valve position, radiation/flux, and coolant chemistry. A large body of literature is available on the emerging and future technology trends in OLM sensors and systems, both for enhancing operational reliability for the current fleet of light water reactors (LWRs) and for the next generation of reactors.[1] Existing OLM systems operate primarily as fault-detection systems. They are used to monitor instrument channel performance and for calibration assessments (i.e., sensor validation tools).[2,3] Research is being conducted on more advanced OLM systems for diagnostics and prognostics that not only detect but also forecast the health of operating machinery. While significant progress has been made in that area, advanced OLM systems have not yet been widely deployed. In addition to monetary factors, structures, systems, and components (SSCs) in existing plants may not be readily adapted to incorporate such new technologies. A number projects in this area are currently being supported by EPRI, DOE, and NRC. It is important to note that while the emerging OLM systems that utilize the available information from the existing plant sensors are expected to improve the reliability in monitoring of active components, health monitoring of passive components remains to be a challenge. Therefore, new sensor technologies and specialized in situ NDE techniques need to be developed in parallel. It is also important to note that while OLM technology used for surveillance, diagnostics and prognostics is expected to play a greater role in monitoring of plant SSCs, it should nevertheless be viewed as a complementary capability to NDE techniques used for condition monitoring and operational assessments that are implemented during periodic ISIs.

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[1] NUREG/CR-6895, "Technical Review of On-Line Monitoring Techniques for Performance Assessment, Vol. 3: Limiting Case Studies," U.S. Nuclear Regulatory Commission, Washington, D.C., 2008.

[2] NUREG/CR-5501, "Advanced Instrumentation and Maintenance Technologies for Nuclear Power Plants" U.S. Nuclear Regulatory Commission, Washington D.C., 1998.

[3] H. M. Hashemian, “Sensor Performance and Reliability,” ISA, 2005.

The second area of application listed above–inspection and monitoring technologies for plant life extension–for the existing fleet of LWR plants is the primary focus of the scoping studies under Task 1. Existing and emerging NDE/NDI technologies for ISI and for in-situ structural health monitoring and damage forecasting are being reviewed. Emerging non-destructive evaluation (NDE) techniques that can provide more efficient (near-real-time) and reliable ISI results will be identified. A non-exhaustive review of the available literature was made on the application of these technologies particularly with regard to corrosion, corrosion-cracking, fatigue, creep, metallic diffusion, and in susceptible materials and components such as similar/dissimilar metal welds, vessel claddings, and concrete. Technologies that could potentially allow in-situ monitoring of crack initiation and growth were reviewed.

Limited scoping studies were also performed on the third area of application listed above–advanced sensor technologies. Attempts were made to identify promising "smart sensor" technologies in application to monitoring of material degradation. Smart sensors in the future are expected to monitor both internal and external stressors and to further provide self-diagnostics capability. They include energy-efficient sensors based on microelectromechanical Systems (MEMS) with embedded artificial intelligence capability. A modest review was also made of the available literature on new wireless sensor (WS) technologies for OLM and condition monitoring. A more detailed review of WS technology is provided in connection with Task 2 activities.

3. Review of Emerging Inspection and Monitoring Technologies

In general, NDE techniques may be used for either material characterization or for ISI of NPP components. When employed for characterization of materials, the most accurate method is commonly selected for a particular application. Alternative NDE methods and destructive examinations may additionally be used for validation and verification of the results. Furthermore, for such applications the efficiency of the examination method is often not a major constraint. For ISI applications, on the other hand, the efficiency (speed of inspection) and cost are often among the main factors that influence adaptation of a NDE method for field deployment. The NDE techniques used for ISI in general provide the means to assess the present condition of a component (i.e., integrity and fitness for service) and to further help predict its performance during the subsequent operating cycle (i.e., meet safety margins). As such, ISI techniques are routinely qualified based on their ability to reliably detect – high probability of detection (POD) – limiting flaws that could become a safety concern to the structural integrity of a component, determined based on mechanistic assessments. In view of the above discussion, it is therefore important to make the distinction between NDE methods used for material characterization and those employed for ISI applications. Accordingly, promising NDE techniques used for accurate characterization of materials in many cases may not be practical for field implementation.

A number of articles and reports have been reviewed in connection with emerging technologies for in-situ and real-time inspection and monitoring of degradation in plant SSCs. Survey of the available literature on conventional NDE technologies employed for ISI applications is outside the scope of this work. A summary of studies on some active areas of research are briefly described below. Examples are provided of emerging and advanced NDE techniques for real-time detection and characterization of early-stage damage and degradation in materials and components.

Emerging NDE technologies in their various forms that can potentially be employed for in situ inspection of NPP components include

- Advances in eddy current testing (ECT) methods including
  - High spatial resolution arrays
  - Thin-film sensors
  - Solid-state sensors including giant and anisotropic magnetoresitive (GMR and AMR) probes
  - Magneto-optic imager (MOI)
  - Pulsed eddy current (PEC) technique
  - Remote-field eddy current testing (RFECT)
  - Superconducting quantum interference device (SQUID)
- Ultrasonic Testing (UT) including
  - Time-of-flight diffraction (TOFD),
  - Phased array UT (PA-UT),
  - Laser UT (LUT),
  - Electromagnetic Acoustic Transducer (EMAT)
  - Nonlinear acoustics/ultrasonics
- Infrared (IR) thermal imaging
  - Pulsed thermal imaging,
  - Thermal tomography,
  - Vibrothermography,
- Enhanced visual testing (VT)
- Micromagnetic methods
- Radiographic testing (RT) with portable instruments
- Radio frequency (RF) and Microwave remote sensing methods

Some promising in-situ NDE technologies for structural integrity sensing in connection with on-line monitoring of material degradation include

- Acoustic emission (AE)
- Active sensing using distributed sensors
  - Inductive probes,
  - Capacitive strain gauges
- Long-range elastic guided wave UT
- Electric potential drop (electrical resistivity probes–DC/AC potential drop (DCPD/ACPD))
- Optical methods
  - Fiber optic sensors (pressure, temperature, strain, radiation, etc.),
  - Digital speckle correlation technique (DSCT) for contact and non-contact measurement of creep, creep-fatigue and strain

Modern NDE equipment has evolved significantly over the past two decades as a direct result of major advancements in microelectronic and computer technology. Some common features of modern NDE equipment include

- Higher degree of inspection automation (hardware and software)

  - More prevalent use of compact and efficient robotic and remotely operated scanners, crawlers, and vehicles for better access in confined spaces
  - Advanced visualization and automated data analysis tools
- Faster inspections through employment of linear and matrix array sensor configurations
- Increased accuracy and quantification capability
  - Improved signal-to-noise ratio (S/N) as a result of improved probe design and on-board signal conditioning electronics
  - Use of advanced and efficient algorithms for real-time analysis of large amounts of data
- Greater penetration depth and higher spatial resolution
- More flexible and modular tools allowing incorporation of multiple sensors in the probe assembly
- Compact systems (integrated inspection units for rapid deployment)
- Rugged probes for operation in harsh environments (elevated temperature and pressure, radiation, moisture, and corrosive media)
- Inspection techniques that are less affected by the surface condition of components

3.1 Emerging NDE Tools

A brief description of a number of emerging NDE technologies with potential application to in-situ inspection and/or monitoring of damage and degradation in passive SSCs is presented next. Only those cross-cutting techniques that could provide improved resolution, penetration depth, accuracy and/or sensitivity are noted here. It is worth noting that the term "emerging" technology here refers to any technique that has not yet gained widespread acceptance for routine field use by the NPP industry, even though the technique itself may have been originally developed and demonstrated in the past.

Eddy current testing in its various forms is among the most widely used NDE methods for examination of electrically conducting materials. A number of emerging ECT methods with the potential to provide improvements over conventional ECT method are noted here. Magneto-optic imaging (MOI) technique combines eddy current excitation with optical imaging techniques to provide real-time visualization of eddy current distribution over a relatively large area. Although the technology has been in use by the aerospace industry for many years (see Fig. 1),[4] its application to the NDE of NPP components has been limited mostly to laboratory tests. Perturbation of induced currents due to surface and subsurface material discontinuities are detected by a magneto-optic sensor in response to the external magnetic fields. The images produced by earlier MOI systems were considered qualitative in nature and with limited quantitative characterization capability. Detection of cracks under protective coating in steel components (e.g., reactor pressure vessel) with a specialized MOI system that uses rotating in-

Figure 1. Industrial MOI system for inspection of aging aircrafts. [*Shih et al*]

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[4] *W.C.L. Shih, G.L. Fitzpatrick,* AMPTIAC Quarterly, Volume 6, Number 3.

plane magnetization has also been reported in the literature.[5] The article reports successful detection of cracks in steel plates which were imaged through 0.125 inches of stainless-steel cladding. Furthermore, it is noted that the rotating in-plane magnetization method allows detection of cracks of arbitrary orientation. A high resolution MOI system ("eddy current microscope") that uses a laser–supported imaging method has been reported.[6] The experimental optical set-up in that case was comprised of a conventional microscope, a lighting technique, an analyzer, and a CCD sensor. More modern MOI systems employing dedicated linear magneto-optical garnet have been demonstrated to provide more quantitative characterization capability and higher inspection speed.[7]

Pulsed eddy current systems commonly utilize a Hall sensor rather than an induction coil to measure the eddy-current signals, (see Fig. 2). The response of an induction coil drops off with decreasing frequency. The same is not true of Hall sensors where the sensitivity does not change below 100 kHz or so. This is extremely useful when looking for deep penetration where information is contained in the very lowest frequencies. A Hall-device based PEC inspection instrument would be expected to offer a number of advantages over conventional EC inspection systems in the aerospace industry. Through several operational advantages, PEC systems can improve detection capabilities with respect to hidden cracks and corrosion. These operational advantages are (a) deeper penetration through the use of solid-state magnetic-field sensing devices, (b) a broadband system providing the capability to distinguish between flaws in different layers and to compensate for lift-off, and (c) adaptability to work with array sensors, thus providing high resolution and inspection speed. Currently, PEC systems are available as commercial NDE instruments. They have been employed extensively in the past for aerospace applications. The use of PEC technology for inspection of heat exchanger tubing and piping in the nuclear systems has been limited to a few specialized applications. Higher depth of penetration in comparison with conventional ECT and the ability to differentiate signals originating from different interfaces within the test piece renders PEC technology a viable candidate for NDE of thick-wall NPP components.

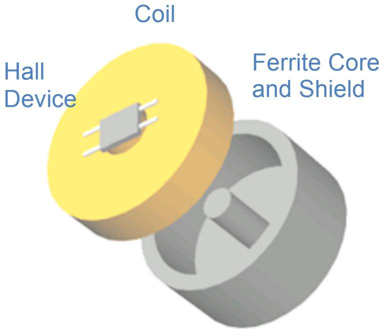

Figure 2. Schematic drawing of a PEC probe developed at Iowa State University. [www.cnde.iastate.edu/NewsandViews/pec%20ver.3.pdf]

A number of eddy current probes employing flexible thin-film sensors and magnetoresistive (MR) elements have been developed for specialized inspection and monitoring applications.[8] The conformable Meandering Winding Magnetometer (MWM®) eddy current sensors may provide alternative inspection capabilities for both steel and non-ferrous alloy components. The sensors provide measurements of

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[5] G. L. Fitzpatrick, R. L. Skaugset, D. K. Thome, and W. C. Shih, "Detection of cracks under cladding using magneto-optic imaging and rotating in-plane magnetization," Proc. SPIE 2947, 106 (1996).

[6] U. Radtke, R. Zielke, H. -G. Rademacher, H. -A. Crostack and R. Herg, "Application of magneto-optical method for real-time visualization of eddy currents with high spatial resolution for nondestructive testing," Optics and Lasers in Engineering, Volume 36, Issue 3, September 2001, Pages 251-268.

[7] J. Pinassaud and P-Y Joubert, "Quantitative magneto-optic imager for nondestructive evaluation," Proc. SPIE 5768, 196 (2005); doi:10.1117/12.598667.

[8] S. Bakhtiari, J-G Sun, K. Wang, "Enabling NDE Technologies for Steam Generators in Advanced Reactor Systems," ANL-GenIV-169, Sept. 2010.

absolute electrical conductivity or magnetic permeability, which can be correlated with many material conditions of interest. Other emerging technologies that could potentially provide improvements over conventional coil-type probes include solid-state giant magneto resistive (GMR) and anisotropic magnetoresistive (AMR) sensors. They offer the potential for development of highly sensitive and low-noise detector elements for low induction sensing applications. The small size probes offer high spatial resolution with deep probing capability. The sensors are fabricated using photolithographic techniques and can effectively be configured as flexible linear and matrix arrays for rapid high-coverage imaging of arbitrary-shaped objects.

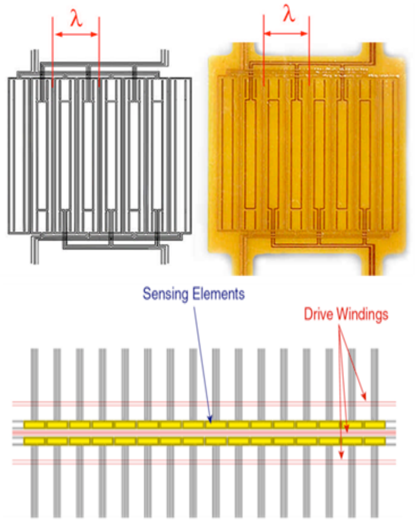

Figure 3. (top) Single sensing element MWM sensor and (bottom) MWM array design (*Jentec® Sensors Inc.*).[11]

The MWM is an inductive, eddy current sensor designed specifically for nondestructive material characterization. The windings of the MWM sensors (see Fig. 3), resembling a square wave, are designed to produce a spatially periodic field.[9,10,11] The sensors are fabricated on a thin and flexible substrate using micro-fabrication techniques, producing essentially identical conformable sensors with essentially identical performance. The repeatability of the MWM sensors provides an important advantage over coil type eddy current sensors, for which nominally identical probes have been found to produce output signals that could differ measurably. Suggested inspection applications with MWM include detection of surface and subsurface cracks on complex parts, metallic and nonmetallic coating thickness and porosity measurement, thermal degradation monitoring, and imaging and detection of small inclusions and voids. Potential applications of MWM sensors include; estimation of residual stresses in low-alloy steel with high magnetic permeability including bidirectional permeability measurements, assessment of fatigue damage assessment in austenitic stainless steel specimens and parts prior to formation of cracks, by monitoring formation of martensite of deformation, and detection and imaging of surface and subsurface hidden cracks in austenitic stainless steel parts. MWMs and MWM-Arrays can also be permanently mounted on operating components in difficult-to-access locations, providing that installation of MWM sensors or MWM-Arrays with cables running to connectors at accessible locations is acceptable. Investigations have also been conducted on MWM array sensors for in situ monitoring of high-temperature components in power plants.[12] In combination with specialized signal processing and data analysis methods such as

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[9] Zilberstein, V., M. Fisher, D. Grundy, D. Schlicker, V. Tsukernik, V. Vengrinovich, and N. Goldfine, "Residual and Applied Stress Estimation From Directional Magnetic Permeability Measurements With MWM Sensors," Journal of Pressure Vessel Technology, 124, 375-381, August 2002.

[10] V. Zilberstein, K. Walratha, D. Grundy, D. Schlicker, N. Goldfine, E. Abramovici and T. Yentzer, "MWM eddy-current arrays for crack initiation and growth monitoring," International Journal of Fatigue, Volume 25, Sept.-Nov. 2003, Pages 1147-1155.

[11] L. C. Wilson, "Characterization of Solid Oxide Fuel Cell Components Using Electromagnetic Model-Based Sensors," final report for DOE under Phase I SBIR Contract No. DE-FG02-03ER83690, Sept. 2004.

[12] Y. S., D. Grundy, V. Zilberstein, N. Goldfine, and S. Maley, "MWM-Array Sensors for *In Situ* Monitoring of High-Temperature Components in Power Plants, IEEE Sensors Journal, Vol. 9, No. 11, Nov. 2009.

measurement-grid based inversion methods for absolute property measurements, MWM sensors could potentially provide alternative inspection capability to conventional ECT coil-type probes. Their applicability to the inspection of NPP components, however, remains to be demonstrated.

Eddy current array probes employing thin-film technology have also been developed for ISI applications. The system developed by the Mitsubishi Heavy Industries (MHI), Inc., is shown in Fig. 4. Similar to other ECT array systems developed for steam generator (SG) tube inspection (e.g., X-probe® by Zetec, Inc.), the probe provides high-speed inspection comparable to bobbin probes while it provides circumferential coverage with a spatial resolution roughly one third of that provided by rotating ECT probes. A typical MHI array probe for examination of 0.875-in.-diameter tube contains 24 drive and pick-up coils that are arranged in a bracelet configuration and provide a 360° circumferential coverage.[13] Only the detector/pick-up coils are manufactured using thin-film technology. The electronics including the multiplexer are all encapsulated within the probe head that can help improve S/N. The probe is non-surface-riding, which is expected to improve its life as a result of eliminating wear associated with friction with the tube inner surface. The directional coils are sensitive to defects of arbitrary orientation, while allowing operation either in absolute or in differential mode. Inspection systems using array probe technology inherently generate large amounts of data. Although a number of array probes have been qualified for field use, the more widespread acceptance of such technology in the future will depend on the development of automated data analysis software for reliable and efficient processing of data.

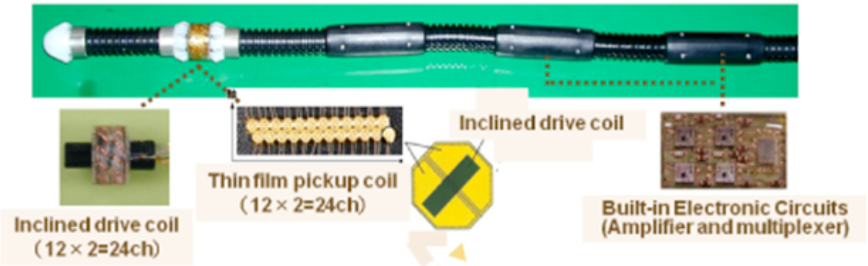

Figure 4. Thin-film array probe (Intelligent Probe®) developed by the Mitsubishi Heavy Industries, Inc., for inspection of SG tubes in PWR plants.

Deeper penetration depths can be achieved by operating at lower excitation frequencies. The sensitivity of coil-type probes on the other hand decreases significantly at lower test frequencies. Magneto-resistors, Hall elements, flux gate sensors and superconducting quantum interference device (SQUID) sensors are potential alternatives to increase sensitivity at lower frequencies. Inspection systems based on some of these promising technologies, however, have not yet been developed for field applications. Further research and development is needed to reduce the complexity and costs of such systems and to further demonstrate their robustness and spatial resolution for practical applications.

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[13] "The Latest MHI Inspection Technology for PWR Nuclear Power Plants in Japan," E-Journal of Advanced Maintenance (EJAM), Vol.1.No.3, OT7, 2010.

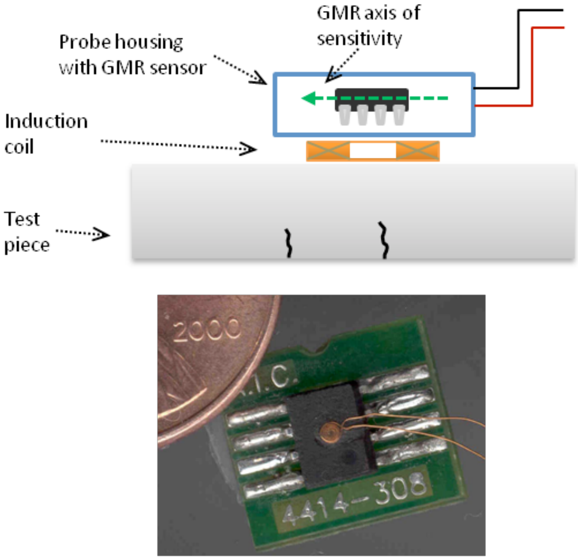

Figure 5. (top) Schematic of a GMR-based sensor for magnetic field sensing and (bottom) picture of a circuit board mounted element. [http://www.dtic.mil/dtic/tr/fulltext/u2/a426287.pdf]

Commercially available AMR and GMR sensors have been used in eddy current probes for low frequency testing.[14] It has been demonstrated that the read out electronics for these MR type sensing elements can be placed into the sensor housing together with the power supply necessary for sensor excitation and read out electronics. Magnetic field Sensors can effectively sense the magnetic field generated by a current carrying conductor or the secondary fields generated by induced currents in a test piece (see Fig. 5). The NVE® Corporation has developed commercially available sensors making use of the GMR technology. The output of their GMR sensors is frequency insensitive up to 1 MHz. High resistivity GMR material allows fabrication of sensors with high resistance (around 5 kΩ). Such sensors can also be fabricated with built-in offset at zero field that provide for a zero crossing in output at a specified field value. A number of publications are available on the use of GMR technology for detection of corrosion and fatigue in infrastructure components. For example, the use of magnetic sensing approach employing GMR gradiometers is reported for measuring both the rate and the extent of corrosion in metal samples.[15] The technique has the potential to overcome some of the difficulties faced by traditional NDE techniques. Active and passive configurations are used for remote monitoring.

Single-element and array ECT probes using solid-state AMR sensors are being investigated as potential replacements for traditional wound wire coils for detection of deeply buried defects inside metal components. The sensors are fabricated utilizing photolithographic manufacturing which allows production of monolithic, high performance, cost-effective, sensors with high degree of uniformity of array probe elements. GMR sensors have greater output than conventional AMR sensors or Hall effect sensors, and are able to operate at fields well above the range of AMR sensors. In addition, high fields will not “flip” GMR sensors or reverse their output as is possible with AMR sensors. High fields will also not cause damage to NVE GMR sensors, as is the case with some competing GMR sensor products.

SQUID detectors have also been used in a number of NDE applications. These devices are considered as the most sensitive detector of magnetic flux. A comprehensive review of published research in NDE performed with SQUID magnetometers is presented by *Jenks et al.*[16] The sensitivity of SQUID instruments over a wide range of frequencies allows them to function as deep-penetrating eddy-current sensors. Their wide dynamic range allows imaging of defects in conducting and ferromagnetic materials

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[14] G Mook, O. Hesse, and V. Uchanin, “Deep Penetrating Eddy Currents and Probes,” ECNDT 2006 - Tu.3.6.2.

[15] John S. Popovicsi, , G. E. Gallo, P. L. Chapman, “Corrosion monitoring of metals through magnetic sensing,” NDTCE’09, Non-Destructive Testing in Civil Engineering, Nantes, France, June 30th – July 3rd, 2009.

[16] W. G. Jenks, S. S. H. Sadeghi and J P Wikswo Jr., “SQUIDs for nondestructive evaluation,” J. Phys. D: Appl. Phys. **30** (1997) 293–323.

with high sensitivity. Over the past two decades, SQUID instrumentation has been designed specifically for NDE applications. Due to a number of engineering challenges, the use of this technology so far has been limited mostly to laboratory tests. New SQUID systems, however, are beginning to emerge with the potential to evolve into practical NDE tools for field applications (see Fig. 6). Examples include the SQUID array developed for the measurements of hidden corrosion in aging aircraft (Tristan Technologies, Inc.). The laboratory magnetometer instrument incorporates a two-dimensional array of detectors for quantifying the rate at which various forms of corrosion damage accumulate in a range of aerospace structures. High scanning speed allows more precise measurement of spatio-temporal changes in a material.

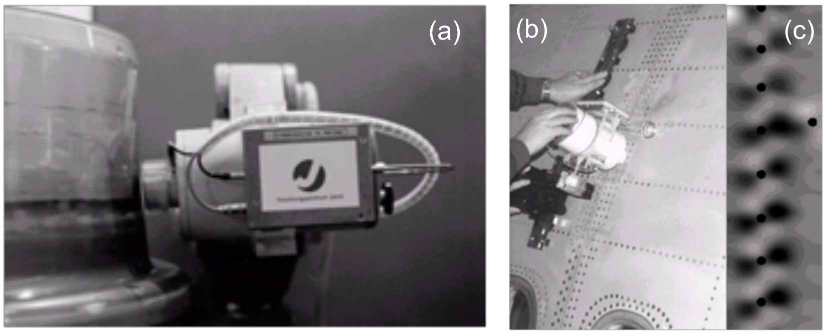

Figure 6. (a) SQUID mounted robot for automated aircraft wheel testing, (b) flexible fuselage scanner system, and (c) image of a section of fuselage with a row of rivets marked by dots [*http://www.ndt.net/article/ecndt98/aero/043/043.htm*].

The discontinuities in solid materials can change the heat flow pattern and in turn result in the fluctuation of the temperature on the surface of the material. Thermal imaging techniques use this principle to measure the change of the surface temperature, which could be related to the condition of discontinuities present in the material. Infrared (IR) tomography (pulsed thermal imaging, thermal tomography, and vibrothermography) have been used an NDE method in a wide range of on-line inspection applications for condition monitoring of electrical equipment, power plant machinery and high-temperature equipment. [17] An infrared camera is commonly used as the detector device. Reported applications include monitoring the condition of insulation and heat loss for high-temperature pressure pipes, heat transfer in heat exchangers, detection of defects in composite pipes, leakage test for underground concrete pipes, assessment of steel plates using pulsed phase thermography, etc. Limited investigations

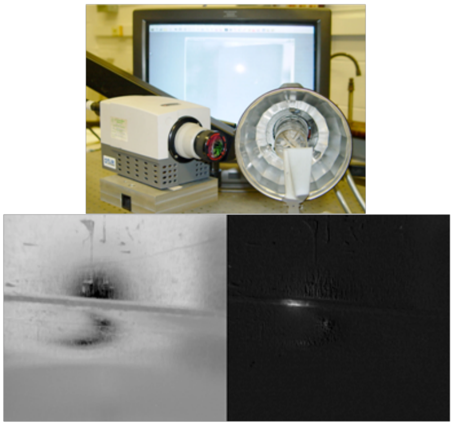

Figure 7. (top) Vibrothermography system at ANL for inspection of welds. (bottom) Raw thermal image of the weld zone (left) and differential image (right) displaying only the reflection from an embedded crack.

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[17] G. Shen and Tao Li, “Infrared Thermography for High Temperature Pressure Pipes,” PetroMin Pipeliner magazine, APR-JUN 2010.

have also been conducted on the use of IR tomography for detection of wall loss defects in steel pipes.[18,19,20] Transient thermography uses inductive heating of electrically conducting materials to detect flaws (disbonds, delaminations and cracks). Compared to conventional flash thermography, the equipment is typically more compact and provides higher efficiency in energy delivery. Commercial systems are available that deliver up to 2 kilowatts of RF energy in a pulsed mode. Vibrothermography is another promising technique for detection of defects in welded joints (see Fig. 7). Reported applications of this technique have been primarily in the automotive and in the aerospace industry. Limited number of investigations, however, has been reported on application of vibrothermography for detrection of damage and degradation in NPP components.

Ultrasonic examination is widely used for a variety of applications within power stations.[6] In general, any application requiring volumetric coverage or examination of inaccessible surfaces is a candidate. Ultrasonic examination has the capability to locate, size, and characterize (that is, determine if the indication is continuous, planar, round, and so on) discontinuities or flaws. This NDE method has been used to verify construction quality (looking for laminations, weld flaws, insufficient wall thickness, and so on). For periodic in-service examination, wall thickness, steam-side oxide scale thickness (used to estimate the local metal temperature and long-term overheat—that is, creep life), microstructural damage (for example, hydrogen damage), and crack-like flaws can be located, characterized, and sized using ultrasonic techniques.

Ultrasonic examination technology encompasses a wide range of applications that vary dramatically in technological sophistication, complexity, required equipment, implementation constraints, speed of application, detection reliability, sizing accuracy, and requisite operator skills. As a general description, ultrasonic examination can be defined as the introduction of high-frequency sound waves, generally in the low-megahertz (MHz) range of 0.5–50 MHz, into a component, part, or structure for the purpose of determining some characteristic of the material from which the component, part, or structure is made. Material characteristics that can be (and have been) determined ultrasonically include material structure, stress (both residual and applied), hardness, anisotropy, and others. However, for power plant examination, ultrasonic examination is used primarily for flaw detection, classification, sizing, and dimensional measurement (thickness). The ultrasonic scan systems provide detailed data for wall thickness and defect location, but they are generally slow. Research is being conducted on using surface or Lamb waves to probe coverage over the entire length of a component.

Probably 75% of all ultrasonic examinations performed in power plants involve conventional shear wave or longitudinal wave techniques.[21] The term "conventional" is used as a descriptive term for pulse-echo or pitch-catch examination using broad beams. However, these techniques have been found to be unsuitable for certain applications—in some cases even for detection, but more often because of

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[18] X Maldague, 'Pipe inspection by infrared thermography', Materials Evaluation, Vol 57, No 9, 1999.

[19] R N Wurzbach and D A Seith, 'Infrared monitoring of power plant effluents and heat sinks to optimize plant efficiency', Proceedings of SPIE – The International Society for Optical Engineering Thermosense XXII, Orlando, FL, USA, 24-27 April 2000.

[20] C Ibarra-Castanedo, N P Avdelidis and X Maldague, 'Qualitative and quantitative assessment of steel plates using pulsed phase thermography', Journal of Materials Evaluation, 63(11), pp 1128-1133, 2005.

[21] EPRI, 2007a, Guidelines for the Nondestructive Examination of Heat Recovery Steam Generators: Revision 1, EPRI, Palo Alto, CA, 2007, 1012759.

unacceptable sizing error. In certain instances, flaw detection is inadequate because sufficient beam intensity cannot be produced in a conventional examination mode to detect the flaw of interest. This is normally attributable to flaw orientation (misorientation) relative to the achievable beam angle and/or is simply because detection requirements are beyond the detection capabilities of this type of examination, as affected by certain material characteristics including material attenuation. To address these detection and sizing limitations, a number of application-specific techniques and special transducers are required. Three types of transducers, focused, phased array, and EMAT are briefly described below.

Focused beam examination provides both improved detection and improved size determination. Specifically, increased beam intensity, achieved by focusing the otherwise widely distributed energy into a small focal spot, provides increased reflection energy and therefore enhanced detection. If properly focused, backscatter from facets and other flaw surface irregularities can be sufficient for detection, even for flaws whose major orientation causes the specular reflection to be directed well away from the transducer. A focused transducer, as shown in Fig. 8, is used for operation within a fluid (e.g., water). A focusing lens is normally attached to the face of the transducer. The liquid is required to provide coupling between the shaped lens and the component surface geometry.

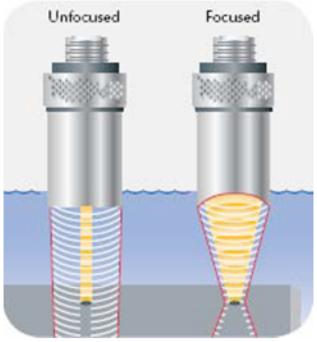
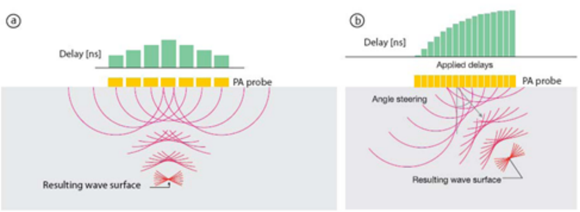


Figure 8. Ultrasonic beam focusing. [http://www.envirocoustics.gr/products/ultrasonic/pdf/Panametrics_UT_Transducers.pdf]

Phased array UT (PA-UT) is another method that is gaining more widespread applicability for inspection of NPP components. An array transducer contains a number of separate elements in a single housing, and phasing refers to how those elements are sequentially pulsed. Each of these elements (typically from 16 to 256) is connected to a separate pulser, receiver, and analog-to-digital converter. These elements are pulsed in such a way as to cause multiple beam components to combine with each other and form a single wave front traveling in the desired direction. Similarly, the receiver function combines the input from multiple elements into a single presentation. Because phasing technology permits electronic beam shaping and steering, it is possible to generate a vast number of different ultrasonic beam profiles from a single probe assembly. Among these, beam steering and focusing are the two basic profiles. The beam steering is achieved when a linearly varying time delay is applied along the array for both excitation (pulsing) and reception, the array then produces an angled sound beam as shown in Fig. 9(a). The angle of the beam is controlled by the delay between adjacent elements and by the acoustic velocity in the propagation medium. On the other hand, if a nonlinear delay function is applied as shown in Fig. 9(b), the sound beam may be caused to focus at a specified distance. Other forms of beam shapes can be produced by the combination of these two basic profiles.



(a) Normal incidence (b) Angled incidence

Figure 9. Synthetic focusing with beamforming.

The benefits of phased array technology over conventional UT emanate from its ability to use multiple elements to steer, focus and scan beams with a single transducer assembly. Beam steering, commonly referred to as sectorial scanning, can be used for mapping components at appropriate angles (This type of image is already familiar to most people; the familiar wedge-shaped, black-and-white ultrasound images of fetuses are sector scans). This can greatly simplify the inspection of components with complex geometry. The small footprint of the transducer and the ability to sweep the beam without moving the probe allows for high-speed inspection as well as aids inspection of such components in situations where there is limited access for mechanical scanning. Electronic focusing permits optimizing the beam shape and size at the expected defect location, as well as further optimizing the POD. The ability to focus at multiple depths also improves the ability for sizing critical defects for volumetric inspections. Focusing can significantly improve signal-to-noise ratio in challenging applications, and electronic scanning across many groups of elements allows for C-Scan images to be produced very rapidly. While significant advancements have been made in this area over the past two decades, it is expected that the emerging PA-UT systems will provide enhanced capability for an increasing number of inspection and monitoring applications for SSCs in the nuclear power industry.

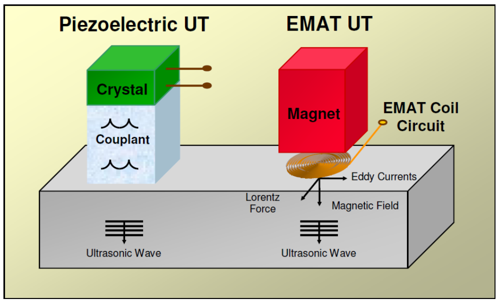


Figure 10. An EMAT UT shown along with a conventional piezoelectric UT. (*Innerspec Technologies, Inc.*)

The EMAT method is essentially a variation of the UT method. In conventional ultrasonic examination, the ultrasonic wave in the component is generated by a form of electromechanical conversion, usually piezoelectricity. This is a highly efficient method of generating ultrasound, but it requires a fluid couplant to mechanically transfer ultrasound into and out of the component. The EMAT technique uses electromagnetic acoustic interaction for elastic wave generation. It generates the sound in the part being inspected instead of the transducer. An inductive element close to the metal surface induces a mechanical disturbance in the metal, which produces the ultrasonic wave. In electromagnetic acoustic generation, the electromagnetic conversion takes place directly within the eddy current skin depth; therefore, no mechanical coupling with the component is needed. The metal surface of the component is its own transducer and the reception of the reflected signal is accomplished in a reciprocal way. This is a major advantage over ultrasonic transducers made with piezoelectric materials that require a coupling medium (typically water). Another advantage of EMAT over UT is that it can tolerate some variation in probe lift-off, so a thorough cleaning of the contacted surface is not necessary. A simple diagram of an EMAT is shown in Fig. 10.

There are other advantages to the use of the EMAT technique. First, it is a nondestructive method with a very high speed and the possibility of being an automated system. It is well suited for large area scans as well as limited access areas where couplant application would be difficult. Also, errors due to couplant variation are eliminated. As no surface contact is required, minimal surface preparation is required and uniform scale layers do not have to be removed. The degree of reproducibility is also high. For the EMAT technique, available special wave modes include surface waves, vertically polarized shear waves, and horizontally polarized shear waves. It is also the only feasible ultrasonic examination method in areas where fluid couplant is prohibited to prevent component contamination.

The disadvantages associated with the EMAT technique are that there is a very high insertion loss (as much as 50 dB) compared to conventional ultrasonic examination. This high insertion loss makes instrumentation design critical. The EMATs receivers are therefore specially designed and expensive units. Also, a substantial power supply is required and the cabling from the power supply to the probe defines the limits of the inspection area. Most utilities rely on consultants and equipment vendors to perform EMAT examinations because of the specialized and expensive equipment required. Utilities can arrange for insulation removal or opening of the unit before the examination. It is also important that sufficient power be supplied to the nearest opening adjacent to the area to be examined. EMAT has been developed to detect various defects in tubes and welding joints. A short list of some past applications of EMAT technique is provided in Table 1.

Laser ultrasonic testing (LUT) is another remote, noncontact extension of conventional UT. A schematic layout of a laser ultrasonic system is shown in Fig. 11. A laser pulse is directed to the surface of a sample through a fiber or through free space. The laser pulse interacts at the surface to induce an ultrasonic pulse that propagates into the sample. This ultrasonic pulse interrogates a feature of interest and then returns to the surface. A separate laser receiver detects the small displacement that is generated when the pulse reaches the surface. The electronic signal from the receiver is then processed to provide the measurement of interest. Laser UT is fast and effective on rough surfaces. It functions effectively in a factory environment. It is ideally suited for many applications including process monitoring and ISI that are beyond the capabilities of conventional UT. The LUT is particularly suited for measurements on parts that are hot and/or moving at high speeds, for high resolution inspections, and for inspection of complex structures and in harsh environments. Currently, most applications of LUT have been associated with the inspection of piping.[22] If integrated with a crawler and wireless technology, compact practical systems could be potentially be developed for various in situ monitoring applications. The main limitation of LUT, however, is its sensitivity to the surface condition of the part under examination.

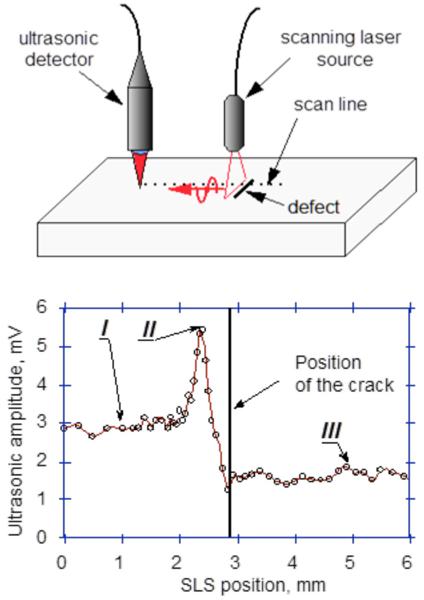


Figure 11. (top) Schematic illustration of scanning laser source (SLS) approach, and (bottom) Typical characteristic signature of ultrasonic amplitude versus SLS location as the source is scanned over a defect [*courtesy of S. Krishnaswamy, Northwestern University*].

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[22] J-R Leea, H. Jeonga, C. C. Cianga, D-J Yoonb, S-S Leeb, "Application of ultrasonic wave propagation imaging method to automatic damage visualization of nuclear power plant pipeline," Nuclear Engineering and Design 240 (2010) 3513–3520.

Table 1.	Some applications of EMAT technique

Experiment Conditions	**Subject**	**In Contact**	**Defects Types**	**Detection Resolution**
1) Non-contact EMAT acting from a remote position and operating by Shear Horizontal (SH) Guided Waves; 2) EMAT probe has a flexible printed circuit coil and suitable array of permanent magnets. Guided SH waves has a frequency between 250 ~ 750 kHz; 3) Over 150 tubes can be inspected in a day.[23]	Heat exchanger tubes (Φ_{in}=10~20 mm), boiler tubes (Φ_{ex}=25~100 mm)	No (Up to 1-mm lift-off can be tolerated)	Bothe volume and surface defects: cracks, sharp notches, denting, inclusions, thickness reduction, corrosion/pitting especially with departing cracks and holes.	Best sensitivity is for sharp cracks with preferred circumferential orientation. Longitudinal defect (1 mm in depth and 20 mm in length)
1) The principal components are a pulsed laser for ultrasound generation and an EMAT for ultrasound reception. 2) The EMAT is designed to be sensitive to incident shear waves arriving at 45° with a frequency range of 0.5 to 20 MHz. The absence of a signal above the threshold level in the calculated time interval indicates a disruption of the sound path by a defect.[24]	Solidified weld metal	No (The pickup coil is about ~0.16 mm or less above the sample)	Weld defects	The EMAT is sensitive to a minimum flaw size of 1 mm in the plane of the ultrasonic wave perpendicular to the direction of weld travel
1) Generation and detection of ultrasonic (US) waves by EMAT probes is based on the interaction between eddy currents and a static magnetic field. When a high current flows through a coil close to the test sample, a Lorentz force is produced in the surface layer, so the lattice structure vibrates at this same frequency, generating	Thickness of aged boiler tubes	No (Up to 1 mm lift-off can be tolerated)	Characterization of the thickness of the tube, and inner/outer oxide thickness	Tube thickness could be evaluated with an accuracy better than 0.2 mm

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[23] Gori, M., S. Giamboni, E. D'Alessio, S. Ghia, F. Cernuschi, and G. M. Piana, Guided Waves by EMAT Transducers for Rapid Defect Location on Heat Exchanger and Boiler Tubings, ENEL/DSR/CRAM G10/95/08, Ultrasonic International 95, Edinburg (UK), 1995.

[24] Carlson, N. M., J. A. Johnson, E. D. Larsen, A. Van Clark, Jr., S. R. Schaps, and C. M. Fortunko, Ultrasonic Sensing of GMAW: Laser/EMAT Defect Detection System, EGG-M-92287.

US waves. Because of the reversibility of such a mechanism, the same transmitting device can be used as a receiver. 2) The measuring assembly is optimized to generate 4 MHz polarized shear waves (SH) and is suitable for steel walls from 2 mm up to 150 mm or more.[25]				
1) A laser-ultrasound/EMAT imaging system for near surface examination of defects. 2) A portable laser-ultrasound system, Nd: YAG laser pulses with energies up to about 15 mJ are used to produce thermoelastic ultrasound. The pulses are delivered to the material surface via an optical fibre and focused to a line source by a cylindrical lens within a scanning head. 3) The same head contains a miniaturized in-plane EMAT receiver, separated by a fixed distance (40 mm) from the optical fibre. 4) Signal capture and process routines are used to generate B-scan images of the test sample. Images reveal a range of ultrasonic transients. They include surface skimming longitudinal (Ls), Rayleigh waves, bulk longitudinal (L) and bulk shear (S) waves. [*Dewhurst et al, 2002*]	Aluminum blocks	No	Surface break slots (0.5 mm wide, 1.5 and 3.0 mm deep)	The in-plane EMAT used here demonstrates that it is more sensitive to any Rayleigh wave that has turned through a 90 corner, as well as any diffracted in-plane shear waves.

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[25] Gori, M., S. Giamboni, E. D'Alessio, S. Ghia, and F. Cernuschi, EMAT Transducers and Thickness Characterization on Aged Boiler Tubes, ENEL/DSR/CRAM G10/95/08, Ultrasonic International 95, Edinburg (UK), 1995.

Guided ultrasonic waves have many useful properties that can be exploited for inspecting large-area structures. The waves can propagate over long distances and provide information about the structure all along the path. Measurements can be made in either pitch-catch or pulse-echo configurations. The elastic waves follow the curvature of an structure and can be directed along any desired helical path from circumferential to longitudinal. Moreover, as the guided waves propagate, they interrogate the entire thickness of the wall in a complex elastic deformation and recovery so that they are sensitive to flaws on the inner diameter, outer diameter and in between. They can be launched and received by externally mounted transducer belts, internal pigs, and by a wide variety of contact and non-contact transducer configurations. Ultrasonic guided waves are becoming more commonplace in industry because of the tremendous advances being made in the mathematics and mechanics of wave propagation that allows us to understand the unusual behavior characteristics that could become a major benefit in ultrasonic non-destructive testing methodologies.[26]

Figure 12. Prototype EmatScan CD pig for inspection of pipelines. Also shown (top corner) is the SH-wave probe in a spring loaded suspension [*http://www.ndt.net/article/wcndt2004/pdf/non-contact_ultrasonics/599_salzburger.pdf*].

Wave modes such as Shear Horizontal (SH)-waves and the wide class of guided waves offer new solutions for UT.[27] For pipelines, Ultrasonic inspection tools are not yet wide spread due to the difficulties of dry coupling using conventional piezoelectric probes. Limited inspections have been done using wheel probes. The dry-coupled EMAT technology offers the potential for high-speed inspection of pipelines. The operability of such systems for field applications is currently under investigation. Within a feasibility study it was shown that guided SH-waves propagating in the pipe wall in circumferential direction have a very high sensitivity for longitudinal crack-like defects and crack fields (SCC) independent from their location (outside or inside). Furthermore it was shown that by proper selection of the frequency the whole circumference of a pipe (36-in. diameter) can be covered by few SH-wave probes. By additional use of Rayleigh waves propagating at the inside surface as well discrimination between inside and outside defects as a defect sizing based on amplitude criteria is possible. Based on these results the concept of the EmatScan CD was developed. In close cooperation with the customer the pig was manufactured and tested. The completed pig can be seen in Fig. 12 during the preparation of a test-run. Also shown in that figure is the final version of the SH-wave probe with optimized wear protection together with a spring loaded suspension.

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[26] J. L. Rose, "Ultrasonic Guided Waves in Structural Health Monitoring," Key Engineering Materials Vols. 270-273 (2004) pp. 14-21.

[27] H. J. Salzburger, "EMAT's and its potential for modern NDE - State of the art and latest applications-," IEEE International Ultrasonics Symposium Proceedings, 2009.

3.2 Inspection of Buried components

Buried pipes are integral part of both safety and non-safety systems of nuclear power plants (NPPs). Degradation of buried piping is an on-going concern with regard to long-term sustainability of light-water reactors (LWRs). Guidelines for maintenance of buried pipe and pipe support structures is included in the NRC Inspection Procedure 62002.[28] Guidelines for management of underground piping and tanks are also provided in NEI 09-14.[29] Inspection of buried piping, however, may not be part of the plant's predictive maintenance program (condition monitoring, surveillance, and testing). Inspections and subsequent repairs or replacements are typically performed either when deemed necessary (e.g., following a leakage incidence) or carried out on a sampling basis to satisfy the regulatory requirements for license renewal. Improved preventative maintenance programs are currently under consideration to address potential safety concerns associated with extending the life aging LWRs in the United States.

Nuclear plant systems that contain buried lines include service water, circulating water, fire protection, diesel fuel oil, spent-fuel pool cooling water, and yard drains.[30] Most buried pipe is made of carbon steel material. Other less commonly used materials include reinforced concrete, cast iron, copper nickel, aluminum, and fiber-reinforced plastics. The source of corrosion of metal pipes can be generally categorized as wall thinning (electrochemical effects), environmental cracking (inter- or trans-granular cracking), and metallurgical effects (change in microstructure or mechanical properties). Cathodic protection systems, coatings, and linings have been used to control surface corrosion of metal pipes and the associated support structures. Failure of the cathodic protection systems has been found in some cases as the primary source of accelerated corrosion. Although the majority of known degradation mechanisms for buried pipes are considered as non-aggressive, as plants age, the number of incidences of leakage nevertheless are expected to increase.

A wide range of NDE methods (both surface and volumetric examination) are currently being used to inspect buried pipes and tanks.[31] Applicability of any particular inspection method is dependent on the condition of the part, its accessibility, and the expected type of degradation mechanism. Conventional NDE methods for inspection of buried or underground piping that require either excavation or entry (i.e., access to inner or outer surface of pipe wall) include

- Visual testing (VT)
- Liquid penetrant testing (PT)
- Magnetic particle testing (MPT)
- Ultrasonic testing (UT)
- Guided-wave UT (GW-UT)
- Radiographic testing (RT)
- Pulsed eddy current testing (PEC)

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[28] *Inspection of Structures, Passive Components, and Civil Engineering Features at Nuclear Power Plants*, Nuclear Regulatory Commission, NRC Inspection Manual, Inspection Procedure 62002, 1996.

[29] *Guideline for the Management of Underground Piping and Tank Integrity*, NEI 09-14 [Rev 1], Dec. 2010.

[30] *An Assessment of Industry Needs for Control of Degradation in Buried Pipe*. EPRI, Palo Alto, CA: 2008. 1016276.

[31] Recommendations for an Effective Program to Control the Degradation of Buried and Underground Piping and Tanks, EPRI, Palo Alto, CA, 2010. 1021175.

Typical NDE methods deployed using pipeline inspection gauges (pigs) for periodic inspections include

- Pulsed eddy current testing
- Magnetic flux leakage
- Remote-field eddy current (RFEC)
- Ultrasonic testing

Inservice inspection methods for Class 1, 2, and 3 piping are included in Sec. XI of the ASME Pressure Vessel and Piping Code.[32] A series of recommendations to improve reliability and safety of buried pipe that include inspection technology and mitigation strategies is provided in EPRI TR-1016276. Visual inspection technology using fiberscopes, borescopes, and video crawlers and submersibles is among the most common nondestructive examination (NDE) method for inspection of buried pipes. Video inspection techniques can be used detect and locate visible corrosion damage and leaks. The capability of video systems is inherently affected by the surface condition of the component and optical transparency of the surrounding liquid for submersible systems. No-dig methods are also employed to determine the likelihood of corrosion in pipe based on the measurement of soil corrosivity characteristics. The characteristics include soil resistivity, pH, sulfides, redox potential, and moisture. Electrical potential survey methods have also been employed to determine the likelihood of major corrosion damage in both cathodically protected and non-cathodically protected pipes. Soil-side corrosion in non-cathodically protected pipes may be estimated by identifying anodic regions along the pipelines. The direct current voltage gradient (DCVG) method is commonly employed for this purpose. For cathodically protected underground pipes, inspection methods include DCVG, close interval potential survey (CIPS or CIS), Pearson survey, and AC attenuation survey. Direct assessment of electrochemical corrosion reaction is generally performed by measuring pipe to soil and structure to soil potentials (direct or alternating current excitation) using a wide range of electrodes and ground contacts. Leak detection techniques are among the most commonly used external methods for detection of pipe failures. An overview of the existing and emerging underground pipeline inspection and monitoring techniques is provided next. A survey of leak detection instruments and techniques for external inspection of piping systems is provided in the following section of this report.

No Dig (Above Ground) Pipe Inspection Techniques — Electromagnetic potential gradient method, commonly referred to as Pearson survey, is a surveying technique used for remote detection of damage to pipeline coating. A closed circuit is formed by attaching a low frequency current exciter to the pipe and grounding the other side. The operator then maps the uniformity of the electromagnetic field above ground as a function of the distance to the pipe connection station. Any field gradients generated by extensive damage to the coating can be detected and located. The main advantages of the electromagnetic potential gradient method include its ability to locate the depth of damaged pipe and eliminating the need for excavations. The disadvantages of the technique include its inability to provide quantitative information about the extent of damage and the influence of buried metallic object in the vicinity of the pipe on the measured signal.

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[32] *Rules for Inservice Inspection of Nuclear Power Plant Components*, Pressure Vessel and Piping Code, Section XI, American Society of Mechanical Engineers, New York, NY.

Guided wave UT (GW-UT) is another attractive method for interrogating long sections (up to 100 feet) of underground piping. Access locations along the length of the pipeline, however, are needed for implementation of GW-UT method. The main advantages of GW-UT technique are thus the ability to examine pipes from above the ground and the ability to get precise positional information about potential flaws and discontinuities along the pipe length. The main limitations of GW-UT technique are lack of flaw sizing accuracy, influence of coatings and soil compaction on detection range, inability to accurately resolve closely spaced defects, and distortion of signal due to presence of discontinuities (elbows, tees, valves, etc.) along the pipe length.

Internal Pipe Inspection Techniques — As noted earlier, a number of NDE methods are available that can be applied through employment of pigs. Inspection vehicles mounted with UT probes are commercially available for internal examination of buried piping. More recently, instrument-mounted pig systems have been developed for applications specific to the NPP pipelines. The available systems, however, are limited to certain diameter piping. The UT instruments commonly operate in a pulse-echo mode and the probe head is composed of multiple transducers that provide 360° circumferential coverage of the pipe diameter. The main advantages of UT inspection systems include accurate wall thickness measurement, high spatial resolution, and rapid inspections. Some known disadvantages of UT systems include sensitivity to surface condition of piping (need for surface cleaning to achieve proper coupling of energy), inability to examine curved surfaced (e.g., elbows), and inability to inspect pipes with internal lining.

Magnetic flux leakage (MFL) is another NDE technique used to inspect ferromagnetic pipes (e.g., carbon steel). In principal, the method detects leakage fields generated by discontinuities in the magnetized test piece. The main advantages of the MFL method are that it is non-contact, provides high spatial resolution, is relatively insensitive to presence of deposits and coatings, and can provide for rapid inspections. The disadvantages of MFL technology include complexity of signal interpretation, directional sensitivity, need for surface cleaning, inability to inspect pipe sections with linings and sharp transitions (e.g., elbows), and bulky equipment (see Fig. 13).[33]

Figure 13. A typical MFL pig.[33]

Pulsed eddy current (PEC) technique, also referred to as broadband electromagnetic method (BEM), may also be deployed by pigs for inspection of underground pipes. The method provides volumetric measurement of wall thickness and in turn provides information about the general condition of the pipe wall. Although the technique does not require a coupling, the eddy current probe must be held at close proximity to the surface of the part under examination. Array probe designs may be employed both to increase the speed of inspection and complete circumferential coverage. The detection of flaws by PEC methods in principal is similar to that of conventional eddy current induction sensing. The difference is that unlike multiple frequency eddy current excitation, PEC method uses a narrow pulse (broadband frequency) for excitation of currents inside the tube wall. The change in the amplitude and the phase of the induced currents may then be measured to determine the thickness as well as the presence of flaws within the pipe wall. The main advantages of PEC (or BEM) method for inspection of buried

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[33] http://netl.doe.gov/technologies/oil-gas/publications/Status_Assessments/71702.pdf

pipes include the non-contact nature of the technique, insensitivity to dimensional variation of piping (curvatures, elbows, etc.), ability to measure through coatings, insensitivity to probe misalignments, and ease of data interpretation. The limitations of the PEC technique include its lack of sensitivity to highly localized defects, influence of probe lift-off, and the need to calibrate the system for different pipe wall thicknesses and material properties.

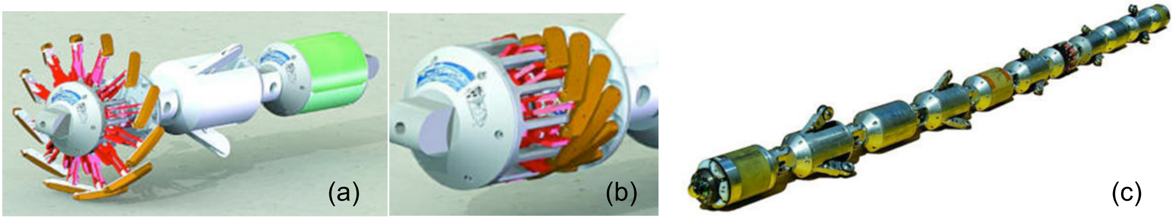

Figure 14. (a) Schematic showing the SwRI-developed RFEC modules. The system consists of two modules, one containing an array of sensors (left) and an excitation coil (right) with the robot centering module in between. The sensor may expand to a 6- or 8-inch diameter for different pipeline sizes and (b) it collapses to 4 inches for traversing bends and for launching. (c) The RFEC inspection technology is fitted into a robotic transport tool. The National Robotics and Engineering Consortium at Carnegie Mellon University developed Explorer II to inspect 6- to 8-inch-diameter pipelines that are not inspectable with current technology. This technology was further developed by Invodane Engineering and has been commercialized by Pipetel Technologies Inc. [http://*www.pipetelone.com*]

Remote-field eddy current (RFEC) testing is another NDE method that is deployed with pigs. An RFEC inspection technology, which can detect and characterize pipeline defects such as corrosion, deployed using a robotic transport tool is shown in Fig. 14. A typical RFEC probe consists of a circumferentially wounded single exciter coil and either single or multiple pickup elements placed at a fixed distance from the exciter. In principal, the presence of any discontinuity in the pipe wall results in perturbation of induced fields which may then be detected by the sensing elements. The use of multiple exciter and sensing elements allows deduction of circumferential position of flaws within the pipe wall. The main advantages of RFEC include the non-contact nature of the technique, its insensitivity to the presence of deposits, coatings, and liners, its ability to inspect tight bends, and light-weight instruments. The main limitations of the technology include slow speed of inspection and inability of RFEC method to discriminate between internal and external defects.

On-line monitoring of extent and rate of corrosion can be performed using electrical resistance (ER) techniques including DCPD and ACPD and, when applicable, using electrochemical techniques such as linear polarization resistance (LPR). The use of guided waves in their various forms for NDE of piping is currently an active area of research. For insulated piping, employment of attachable piezoelectric transducers allows inspections to be carried out with minimal damage to the insulation material. Ultrasonic guided wave technology offers the potential to rapidly detect, locate, and characterize different flaw types and at different regions along the pipe (straight sections, bends, weldments). The emerging ER probe technology also has the potential to provide further improvement for in-situ and continuous monitoring of corrosion in metallic piping and other buried components and structures.

The ER technique is an on-line method of monitoring the rate of corrosion and the extent of total metal loss for any metallic equipment or structure. The ER technique measures the effects of both the electrochemical and the mechanical components of corrosion such as erosion or cavitation. It is considered as the only on-line, instrumented technique applicable to virtually all types of corrosive environments. An ER monitoring system consists of an instrument connected to a probe. The instrument may be permanently installed to provide continuous information, or may be portable to gather periodic data from a number of locations. Conventional ER probes are commonly equipped with a sensing element having a composition similar to that of the process equipment of interest. Reduction (metal loss) in the element's cross section due to corrosion will be accompanied by a proportionate increase in the element's electrical resistance. Practical measurement is achieved using ER probes equipped with an element that is freely exposed to the corrosive fluid, and a reference element sealed within the probe body. Measurement of the resistance ratio of the exposed to protected element is used to deduce information about material loss. Since temperature changes affect the resistance of both the exposed and protected element equally, measuring the resistance ratio minimizes the influence of changes in the ambient temperature. Therefore, any net change in the resistance ratio is solely attributable to metal loss from the exposed element once temperature equilibrium is established.

Scanner systems have been developed that operate based on the well-established ER technique where thinning of a metal increases its measured electrical resistance (see Fig. 15).[34] Due to the fact that the measured resistance is also dependent on the temperature, the new systems have the ability to simultaneously measure temperatures and resistances to a high precision, allowing this temperature dependency to be effectively nulled out. Measurements are performed at, and between, adjacent sensor locations in a pre-defined sequence (i.e sensor arrays) to allow full surface maps to be produced. The scanners allow parameters such as metal loss, corrosion rate, remaining thickness and time-to-replacement to be automatically calculated and mapped. A specialized version of the scanner was developed for use on EPRI-sponsored projects in the USA for detecting crack growth on weld-overlaid boilers tubes. These systems have been installed on supercritical power generation boilers. The thermal monitoring hardware can also operate independent of the ER measurement probe to provide thermal mapping on a real time basis, either as surface temperatures or heat flux.

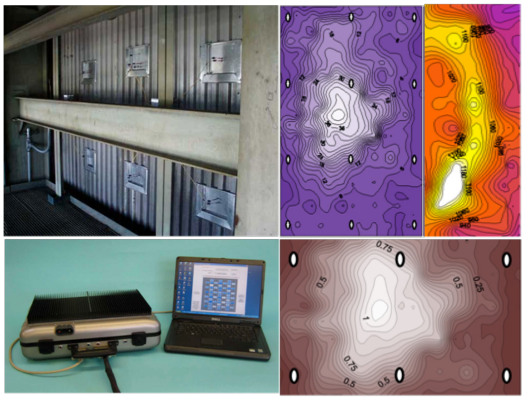

Figure 15. (Top) Fixed system with six scanner electrode that form part of a larger electrode matrix used to map corrosion rate and temperature. (Bottom) A portable system for periodic monitoring (*ROWAN Technologies, LTD*).

The LPR method is used to rapidly identify corrosion upsets and initiate remedial action, thereby prolonging plant life and minimizing unscheduled downtime. The technique is more effective when installed as a continuous monitoring system in almost all types of water-based, corrosive environments. The measurement of LPR has very similar requirements to the measurement of full polarization curves. It uses a series of electrodes, a voltmeter, an ammeter and a current source. The direction of current flow is reversed in the test, causing the test electrode to become the anode with an accelerated corrosion rate. The current level is increased to maintain a constant polarization potential voltage. The corrosion rate is directly proportional to the current level.

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[34] ROWAN Technologies, LTD, http://www.rowantechnologies.co.uk/resistance_scanner_systems.htm.

Figure 16. A guided wave sensor that can perform wall thinning inspection of piping [*courtesy of G. M. Light, SwRI*].

Measurement of wall thinning in piping has, in the past, required the removal of all the heat insulation used to clad the pipes. Guided wave inspection systems have been developed that can screen several tens of meters of pipe for wall thinning at a time but only requires a small amount of heat insulation to be removed. Key features of modern systems include the sensor housing containing piezoelectric or magnetostrictive elements that can be attached directly to the piping and the signal processing tools for improved detection capability. Magnetostrictive devices provide lower profile and are generally less expensive than piezoelectric devices (see Fig. 16). The systems can detect small changes in cross-section area, not only in straight piping but also in small-diameter curved pipes. For large-diameter pipes, a partially attached guided wave sensor is currently under development by Hitachi with the aim of identifying the location of wall thinning within a comparatively small range from the sensor.[35] A proprietary signal processing software is used to significantly improve the detection performance.

3.3 Measurement of Residual Stress

Scoping studies revolved on conventional and emerging techniques used for measuring residual stresses in materials and components. A brief description of the most common techniques used for characterizing residual stress (RS) is provided below. The primary focus of these studies was on NDE techniques that could be employed for in situ characterization of residual stress. A number of conventional RS measurement techniques applicable to in situ measurement of RS in nuclear power plant components are discussed below. Some prominent emerging technologies that could potentially be used for future field applications are also noted.

Residual stresses can have a profound effect on the performance of materials and the structural integrity of components. The measurement of RS is normally complicated by the superimposed and typically less important in service stresses. Therefore, it is important for the measurement method to be able to distinguish between the two types of stressors. The level of information provided by different RS measurement techniques can vary significantly. The selection of a particular measurement method should thus be made in view of its capability under specific set of test conditions. In some cases complementary techniques may have to be used to increase the measurement accuracy and reliability.

Analytical and numerical methods are routinely used to estimate in service stresses on a component. Such calculations are generally accurate when the operating conditions are reasonably well defined. Unavailability of accurate information about the level of preexisting or service-induced RS can result in inaccurate estimation of structural integrity and in turn in prediction of the remaining useful life of components. The possibility of unexpected failures can be reduced through incorporation of measured

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[35] M. Odakura, Y. Kometani, M. Koike, M. Tooma, Y. Nagashima, “Advanced Inspection Technologies for Nuclear Power Plants,” Hitachi Review, Vol. 58 (2009), No.2.

RS values into numerical models. Significant research efforts are also under way toward development of improved numerical multi-physics models for more accurate structural integrity assessments.

Stress measurement techniques can be separated into two general categories of destructive and nondestructive methods. The techniques can vary significantly in their spatial resolution and penetration depth as well as the accuracy they can provide. Destructive methods typically require drilling of holes, sectioning or incremental removal of material layers from a component. Mechanical stress measurement methods monitor the changes in the distortion (stress relaxation) of a component as material layers are removed. Curvature measurements are often used to determine the stresses within coatings and layers.[36] Curvature can be measured to a depth of 0.1-0.5 of the thickness using contact methods (e.g. profilometry, strain gauges) or without direct contact (e.g. video, laser scanning, grids, double crystal diffraction topology), allowing curvatures down to about 0.1 mm^{-1} to be characterized. Hole drilling method is based on the concept that undisturbed regions of a sample containing RS will relax into a different shape when the locality is machined, thereby providing data for the back-calculation of residual stress. The machining operation usually involves drilling a hole around which the strain is measured using either a rosette of strain gauges, moire interferometry, laser interferometry based on a rosette of indentations, or holography. Although it is possible to deduce the variation in stress with depth by incrementally deepening the hole, it is difficult to obtain reliable measurements much beyond a depth equal to the diameter. The crack compliance method involves cutting a small slot to monitor the relaxation of stress in the vicinity of the crack using strain gauge interferometry. By steadily increasing the depth of the slot, it is possible to resolve the stress field normal to the crack as a function of depth for relatively simple stress distributions.

Diffraction techniques employ electron, X-ray, or neutron beams to measure changes in interplanar spacing and using the Bragg equation to detect elastic strain through the knowledge of the incident wavelength and the change in the Bragg scattering angle.[28] The strain results can then be converted into stress using a suitable value of the stiffness for the material under test. Very high lateral spatial resolution can be achieved using electron beams which can be focused to diameters as small as 10 nm. The convergent beam electron diffraction technique is commonly used to achieve the greatest strain resolution. Only very thin samples (<100 nm) can be examined, which naturally renders the results vulnerable to surface relaxation effects and the strain values represent an integral through the thickness. Laboratory X-ray diffraction (XRD) technique, in the wavelength range of $\lambda \sim 0.1 - 0.2$ nm, can be used to measure stress in a very thin surface layer (typically tens of μm). This small depth of penetration means that the sampled region can often be assumed to be in-plane stress and thus obviates the need for an accurate strain-free lattice spacing determination. X-ray diffraction methods are well established and have been standardized by the ASTM and SAE. Accurate measurement of the in-plane macrostress is obtained when the penetration depth is small compared with the scale of the microstructure. Surface removal techniques can be employed to perform depth resolved studies. The practical depth limit, however, is about 1 mm. Errors can arise when measurements are performed on rough surfaces (e.g. welds) using the conventional focusing optics arrangement. Neutron diffraction (ND) can be used to measure stress in a similar fashion as X-ray techniques. Samples sizes are large compared to those used for XRD. Neutrons, however, have the advantage over X-rays that for wavelengths comparable to the atomic spacing, their

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[36] P. J. Withers and H. K. D. H. Bhadeshia, "Residual stress Part 1 – Measurement techniques," Materials Science and Technology, Vol. 17, April 2001.

penetration into materials is typically many centimeters. By restricting the irradiated region and the field of view of the detector by slits or radial collimators, it is possible to obtain diffracted intensity from only a small volume (>1 mm^3), from deep within a sample. There are essentially two ND techniques that have developed largely because of the two forms in which neutron beams are available, i.e. either as a continuous beam from a reactor source, or as a pulsed beam from a spallation source. A detailed description of RS measurement by using neutrons is provided in IAEA-TECDOC-1457.[37] Synchrotron (or hard) X-rays at central facilities have also been used extensively for measurement of stress. Synchrotron sources can be as much as a million times more intense than conventional sources and can provide high energy photons (20 – 300 keV) that are over a thousand times more penetrating than conventional X-rays.

Residual stresses can also be measured by using electrical and magnetic techniques. When magnetostrictive materials are stressed the preferred domain orientations are altered, causing domains most nearly oriented to a tensile stress to grow (positive magnetostriction) or shrink (negative magnetostriction).[28] Stress-induced magnetic anisotropy leads to the rotation of an induced magnetic field away from the applied direction. A sensor coil can monitor these small rotations in the plane of the component surface. When no rotation is observed, the principal axes of the magnetic field and stress are parallel. By rotating the assembly, both the principal stress directions and the size of the principal stress difference can be measured. Magnetoacoustic emission is the generation of elastic waves caused by changes in magnetostrictive strain during the movement of magnetic domain walls and is generally detected from the material bulk. Barkhausen emission on the other hand, is recorded as a change in the emf proportional to the rate of change in magnetic moment detected in probe coils as domain walls move. As the emission is attenuated at high frequencies by eddy current shielding, it may be used as a near-surface (<250 μm) probing method. Magnetic methods are sensitive to both stress and the component microstructure. Calibrated measurements are therefore needed to account for microstructural variations. Magnetic methods provide inexpensive and in-situ NDE techniques for the measurement of residual stress in magnetostrictive materials.

Eddy current (EC) techniques have also been used for measuring RS in materials and components. The method is based on inducing eddy currents in a conducting material and detecting changes in the electrical conductivity and/or magnetic permeability through changes in the test coil impedance. The penetration depth (related to the skin depth) can be adjusted by changing the excitation frequency. The penetration depth in practice is typically limited to around 1 mm. While conventional EC probes cannot identify the direction of the applied stress, specialized probes have been used for directional measurements. Recent work suggests that EC methods can be applied to a wider range of materials than magnetic methods. Eddy current methods in general may not be well suited to basic measurement of RS due to the sensitivity of EC monitoring to such factors as microstructural changes. The method, however, can be employed as a rapid and inexpensive in-line inspection technique.

Thermoelastic and photoelastic methods may also be used to measure RS.[28] The elastic deformation of a material causes small changes in temperature (1 mK for 1 MPa in steel). Using an infrared (IR) camera, it is possible to map the thermal variations in the material that are indicative of variations in stress. The thermoelastic constant, which describes the dependence of temperature on stress,

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[37] "Measurement of residual stress in materials using neutrons, IAEA-TECDOC-1457, June 2005.

allows the hydrostatic stress component to be determined. The effect is rather small, so highly sensitive IR cameras are needed for measurement of thermal gradients. Thermoelastic method is well suited to fatigue studies. The tendency for the speed of light in transparent materials to vary anisotropically when the material is subjected to a stress is termed the photoelastic effect. It gives rise to interference fringe patterns when such objects are viewed in white or monochromatic light between crossed polars. The resulting fringe patterns can be interpreted to give the local maximum shear stress if the stress optic coefficient is known from a calibration experiment. Photoelastic measurements are in general made using two-dimensional epoxy resin models or from slices cut from three-dimensional models in which the stresses have been frozen in. Residual strains arising from dislocation kink bands and long range plastic misfit stresses have been measured photoelastically in ionic AgCl model materials.[1]

Portable XRD instruments have been developed for in situ measurement of RS. Automated systems are commercially available for measurement of RS distributions.[38] One common application of the technique is to quantify subsurface residual stress distributions resulting from the shot peening process that is introduced deliberately to relieve build up of stresses in a component. For such applications, surface residual stress measurements alone could be misleading because the shot peening process can produce high residual stress gradients in the deformed surface layer of material. Therefore, subsurface measurements are often made to fully characterize the RS fields. Residual stress in those cases is measured at different depths through incremental removal of layers of material under test. Alternatively, non-destructive monitoring of RS may be done by performing XRD on coupons (identical material and heat treatment as the component) placed at strategic positions on the component. Residual surface stresses induced by welding and other manufacturing operations play a critical role in the stress corrosion cracking (SCC) of many power plant components. Conventional X-ray equipments are bulky and use high power X-ray tubes. Furthermore, the solid-state X-ray detector leads limit access to confined locations. Research sponsored by EPRI toward development of a compact X-ray system for situ measurement of surface RS is described in various technical reports.[39,40] The reports describes the results of efforts on development a miniature XRD instrument as a NDE tool for surface residual stress measurements in a confined space. Standard X-ray diffraction line broadening analysis is capable of measuring the magnitude of residual stresses, thereby providing an early warning of conditions that might promote SCC. The project investigated the possibility of miniaturizing both the X-ray source and the detectors. A prototype system was assembled by using a commercially available 20-watt X-ray tube (powered at 20 kV and 1 mA) and miniaturized detectors by using a solid state, high- efficiency scintillation detector coupled with a flexible, coherent fiber optics bundle. The scintillation resolution of the CCD fiber optic Ruud-Barrett based position sensitive scintillation detector (PSSD) was used to accommodate for a reduction in X-ray focusing geometry. Residual stress measurements were performed in a 50-mm diameter pipe at a working distance of 20 mm with demonstrated accuracies on the order of 35 MPa. A commercial prototype of the XRD system was later designed and fabricated.[32] In the new design, a ceramic X-ray tube smaller and more stable than the one used previously by Ruud was incorporated into the system along with an improved CCD device. The design was evaluated and improvements were suggested to allow better accuracy for measurements in confined spaces.

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[38] Automated Surface and Subsurface Residual Stress Measurement for Quality Assurance of Shot Peening, LAMBDA Research, NO. 27, Spring 2001.

[39] *In Situ Measurement of Residual Surface Stresses,* EPRI, Palo Alto, CA: 2000. TR-109717.

[40] *Portable X-Ray Diffraction Residual Stress Instrumentation,* EPRI, Palo Alto, CA: 2004. 1004923.

In-situ non-destructive measurement of RS by a photothermal method is described in an EPRI technical report.[41] The report describes a procedure to measure RS in type 304 stainless steel components. The method involves measurement of deformation by laser shearography before and after local stress relief. Detecting these regions of tensile RS in power plant equipment can identify locations of potential SCC. Under EPRI sponsorship, Karta Technology, Inc. evaluated the use of a photothermal method to measure RS. The proposed method determines RS by locally relieving stress using a thermal method, and then optically quantifying the resulting deformation. The technique optically reveals residual stress by detecting deformations that occur on the surface when heated. Processing of the data for the system developed in that program was done by using multiple neural network (NN) algorithms. The system requires capturing of two images of the surface before and after the application of a local thermal input. A trained NN evaluates the residual stress sign and magnitude and can be trained to measure surface RS for different material types and surface conditions. Further research efforts are under way to develop practical photothermal systems for field use.

Ultrasonic techniques have also been investigated extensively for in-situ NDE of RS. As noted earlier, the technique is based on measuring the effect of stress fields on the propagation speed of ultrasonic waves. The residual stress is then calculated by using the acoustoelastic constant to compare the measured velocity to the known value of an unstressed part. Ultrasonic techniques have the potential of providing three-dimensional measurements. The primary disadvantage of this technique is the fact that the velocity of the ultrasonic wave is affected by other factors (e.g., surface condition, texture, and temperature) than the stress present in the material. The possibility of mapping of the stress fields in wall and welds in a mock-up pressure vessel was demonstrated using critically refracted longitudinal (L_{CR}) waves.[42] The L_{CR} wave typically is excited and received with ultrasonic probes attached to plastic wedges inclined at approximately the first critical angle, as calculated by Snell's law. A contoured L_{CR} probe was used in that study and the pressure vessel was fitted with strain gauges for monitoring the wall stress. The results of the investigations showed that at low wall stresses, below 4 ksi (26 MPa), the ultrasonic data exhibited considerable scatter. At wall stresses of 4 ksi (26 MPa) and above, however, there was an almost linear relationship between stress and travel-time change. Measurements adjacent to an end weld also showed very good trends. For example, ttravel times approaching a weld predict 227.5 ksi (2190 MPa) at 1 in. (25 mm) from the weld, compared to zero stress at 5.6 in. (142 mm) away from the weld. The use of L_{CR} waves for characterization of hydrogen induced stress in pipelines is described in another article.[43] The approach was to concentrate the ultrasonic energy in a layer near to the surface of the part where hydrogen buildup is accumulating. The authors, however, point to the fact that each application is unique and material properties such as the acoustoelastic constant are critical. Also, unique probe designs and pressure application systems may have to be designed for different test conditions. Examples of other applications of L_{CR} waves for mapping of stress fields in different components are reported by different groups.[44,45]

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[41] *Measurement of Residual Stresses by Photothermal Method,* EPRI, Palo Alto, CA: July 2000. 1000156.

[42] Don E. Bray, "Ultrasonic Stress Measurement and Material Characterization in Pressure Vessels, Piping, and Welds," ASME, Vol. 124, AUGUST 2002.

[43] Don E. Bray and Richard B. Griffin, "Ultrasonic Characterization of Hydrogen Induced Stress in Pipelines," Proceedings of the 5th International Offshore Pipeline Forum IOPF 2010-6001.

[44] D.E. Bray, W. Tang, "Subsurface stress evaluation in steel plates and bars using the L_{CR} ultrasonic wave, " *Nuclear Engineering and Design* 207 (2001) 231–240.

Ultrasonic systems have been developed specifically for measuring RS under field conditions.[46,47,48] Development of an "Ultrasonic Computerized Complex (UCC)" for NDE of residual and applied stresses is reported by *Kudryavtsev et al*. The UCC includes a measurement unit with transducers and basic supporting software, an advanced database, and expert system software, housed in a laptop, for analysis of the influence of RS on the fatigue life of welded elements. It is stated that the method allows RS to be measured as an averaged value through the thickness of the component or in surface layers. More recent work on the development of ultrasonic NDE methods for in-situ measurement of stress at elevated temperatures is reported in EPRI TR-1021161. The use of an electromagnetic acoustic transducer (EMAT) based system for subsurface measurement of RS was investigated. An important advantage of EMAT over conventional piezoelectric ultrasonic transducers is that the former does not require the use of couplants for excitation and detection of ultrasonic waves. The non-contact nature of EMAT allows measurements to be performed on components under actual operating conditions. The technique is also less sensitive to the surface condition of the part allowing measurements to be performed without surface preparations. The measurements were performed on sheet specimens made of Alloy 600 material. The coupons were subjected to chemical, thermal, and/or mechanical loading. To assess the capability of EMAT, surface characterizations of the in-plane residual stress components were performed using both XRD and ND methods. Investigations under this EPRI sponsored project are associated with measurement of the stress levels to assist with the weld mitigation process. Project results showed that use of an EMAT offers an alternative technique to XRD for obtaining stress measurements in a laboratory environment. Further research efforts are needed toward development of EMAT systems for field use.

Assessment of five NDE techniques for measuring RS is provided in EPRI TR-1019145.[49] Stress measurements were conducted on a set of well-characterized Alloy 600 samples that have undergone changes in material properties resulting from simulated operating conditions, including heat treatment, three-point bending load, cracking, and repair. The overall objective of the project was to identify suitable NDE techniques that would augment the existing and proven surface residual stress measurements by XRD and extend the measurement capability down to below surface. The NDE techniques used to estimate residual stress included optical photothermal measurements, noncontact acoustoelastic measurements by surface wave, contact acoustoelastic measurements by bulk longitudinal waves, contact magnetoacoustoelastic measurements by bulk longitudinal waves during a magnetization cycle, and surface acoustic impedance measurements. Based on the results of those investigations on limited number of samples the optical photothermal technique showed surface residual stress estimates that were comparable to those measured by XRD. None of the acoustic wave-based speed changes correlated to XRD- or ND-based stress measurements. Magnetoacoustoelastic measurements showed promise. No reference data, however, were obtained because of the limited physical size of plate samples. The project results in general showed that continued work is necessary for identifying a more robust technique

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[45] Z. Ling, H. Zhou, and H. Zhang, "Nondestructive Pressure Measurement in Vessels Using Rayleigh Waves and L_{CR} Waves," IEEE Trans. on Inst. and Meas., Vol. 58, No. 5, May 2009.

[46] Y. Kudryavtsev and J. Kleiman, "Measurement of Residual Stresses in Welded Elements and Structures by Ultrasonic Method," Structural Integrity Technologies Inc., IIW Document XIII-2339-10.

[47] Y. Kudryavtsev et al, "Ultrasonic Technique and Device for Residual Stress Measurement," Integrity Testing Laboratory Inc., Ontario, Canada, 2004.

[48] *Nondestructive Evaluation of Residual Stress by Electromagnetic Acoustic Transducers,* EPRI, Palo Alto, CA: November 2010. 1021161.

[49] *Nondestructive Evaluation and Measurement of Residual Stress,* EPRI, Palo Alto, CA: December 2009. 1019145.

affected less by material surface conditions or material texture. Because of significant and measurable acoustic speed changes noted during the magnetoacoutoelastic measurements, this technique should be investigated further with larger samples. Previous investigations suggest that the technique is well suited for evaluating stress from welded Inconel plate samples that exhibited permeability variations.

The use of EC techniques for mapping of stress in various conducting materials has also been investigated.[42-45] Eddy current measurements are capable of mapping the near-surface depth profile of the electrical conductivity. It has been demonstrated that EC conductivity measurements can be exploited for near-surface residual stress assessment in surface-treated nickel-base superalloy components.[50,51] To quantitatively assess the prevailing RS from EC conductivity measurements, the piezoresistivity coefficients of the material must be first determined using known external applied stresses. It is demonstrated in this paper that such dynamic calibration measurements should be corrected for the thermoelastic effect, which is always positive, i.e., it increases the conductivity in tension, when the material cools down, and reduces it in compression, when the material heats up. Both circular (non-directional) and directional racetrack coil probes were used for the load frame testing. The racetrack coils were oriented either parallel or normal to the loading direction to observe the directional dependence of stress on the apparent eddy current conductivity. It was found that the electroelastic coefficients measured by the circular probe were equal to the average of those measured by the directional racetrack probe at parallel and normal orientations. It was noted that although the EC frequency could affect the accuracy of electroelastic measurements, the parallel and normal electroelastic coefficients are essentially frequency independent. The results of subsurface RS measurements based on EC conductivity in surface-treated nickel-base superalloy components is reported by *Bassam et al*. The depth-dependent electric conductivity profile was first calculated from the measured frequency-dependent apparent EC conductivity spectrum.[43] The residual stress depth profile was then calculated from the conductivity profile based on the piezoresistivity coefficient of the material, which is determined separately from calibration measurements using known external applied stresses. The results of those investigations indicate that in some nickel-base superalloys the relationship between the electric conductivity profile and the sought residual stress profile is more tenuous than previously thought. Specialized probes for rapid imaging of conductivity and permeability using directional surface-conforming inductive, magnetoresistive, and EC sensors have also been developed.[52,53] The results of past investigations in general have not clearly established the applicability of EC technique as a general purpose method for RS measurement. It is plausible that EC methods can be adapted to in situ or on-line monitoring of electrical property variations that are indirectly correlated with RS and in service stresses. Further investigations, however, are needed to establish such correlations for practical applications.

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[50] Feng Yu and Peter B. Nagy, "Dynamic Piezoresistivity Calibration for Eddy Current Nondestructive Residual Stress Measurements," J. of Nondestructive Evaluation, Vol. 24, No. 4, December 2005.

[51] Bassam A. Abu-Nabah ·Waled T. Hassan, Daniel Ryan, Mark P. Blodgett, Peter B. Nagy, "The Effect of Hardness on Eddy Current Residual Stress Profiling in Shot-Peened Nickel Alloys," J Nondestruct Eval (2010) 29: 143–153.

[52] Neil Goldfine, Andrew Washabaugh, Vladimir Zilberstein, Darrell Schlicker, Ian Shay, David Grundy, Mark Windoloski, "Absolute Electrical Property Imaging Using High Resolution Inductive, Magnetoresistive and Capacitive Sensor Arrays for Materials Characterization," Proc. of 11th Int'l Symposium on Nondestructive Characterization of Materials, June 24-28, 2002; Berlin, Germany.

[53] Goldfine, N. J., Schlicker, D. and Washabaugh, A., (1998a), '' Surface-mounted eddy-current Sensors for On-line Monitoring of Fatigue Tests and for Aircraft Health Monitoring'', Second Joint NASA/FAA/DoD Conference on Aging Aircraft, USA.

3.4 Inspection of Concrete Structures

Reliable determination of the integrity and the remaining useful life of concrete structures in the existing fleet of LWR plants is an important issue. Degradation in concrete structures can occur in one or all of its components that include the cement matrix, aggregate material, and rebar (in reinforced concrete). The majority of past incidences of degradation in concrete structures in the U.S. have been associated with poor construction practices.[54] Nevertheless, long-term performance of concrete civil structures, particularly those categorized as safety related systems, remains to be a concern. Visual techniques (VT) have traditionally served as the primary inspection method for examination of concrete structures. The wide range of tools and equipment used for visual inspection includes thermometers, anemometers, binoculars, telescopes, borescopes, endoscopes (fiber scopes where access is difficult), microscopes, and cameras (with high zoom, micro lenses, polarized filters, etc). Nondestructive in situ examination and monitoring techniques are gaining more widespread acceptance for periodic inspection of concrete structures. To ensure continued structural integrity of NPPs, research activities are currently under way by EPRI and DOE to identify possible technology gaps for NDE of concrete structures and to ultimately develop more reliable inspection procedures for field applications. A number of factors limit the applicability of existing NDE and OLM technologies to the inspection of civil structures in operating NPPs. They include attributes such as large physical dimensions (e.g., thick-walled, heavily reinforced concrete), close proximity to other SSCs, complex geometry and composition, presence of multiple layers, and access restrictions to hazardous environments (i.e., radiation, contamination, elevated temperatures, etc.).

A large body of literature exits in connection with NDE methods used for inspection of concrete civil engineering structures. A limited overview of the conventional and emerging technologies in application to NPP civil structures is provided here. A description of common NDE methods used for inspection of concrete structures is provided in various IAEA and EPRI technical reports.[46,55,56] A comprehensive overview of inspection and monitoring methods including those used for NDE of concrete structures in NPPs is also provided in a recent PNNL report.[57,58] Table 2 provides a list of NDE techniques used by the concrete industry, a subset of which has been recognized by professional standard committees such as the American Concrete Institute (ACI) and the American Society for Testing and Materials (ASTM). The NDE methods listed in that table may be divided into three general categories according to their applications. The first category includes the methods that estimate the in-situ strength either directly (e.g., penetration resistance and pullout techniques) or indirectly (e.g., surface hardness). The second category includes the methods that measure the material properties of concrete such as moisture, density, compressive wave velocity, modulus of elasticity, thickness, and temperature. The techniques in the second category include ultrasonic, nuclear and electrical methods. The third category comprises of methods used to detect and locate the defect areas within concrete structures and rock

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[54] *Program on Technology Innovation: Concrete Civil Infrastructure in United States Commercial Nuclear Power Plants.* EPRI, Palo Alto, CA: 2010. 1020932

[55] Guidebook on non-destructive testing of concrete structures, IAEA–TCS–17, 2002.

[56] Non-destructive testing for plant life assessment, IAEA-TCS-26, 2005.

[57] D. J. Naus, "Inspection of Nuclear Power Plant Structures – Overview of Methods and Related Applications," ORNL/TM-2007/191, 2009.

[58] D. J. Naus, "The Management of Aging in Nuclear Power Plant Concrete Structures," JOM, Vol. 61, No.7 pp. 35-41, 2009.

masses such as honeycombing, fractures, flaws and delaminations. The techniques in that category include impact-echo, ground penetrating radar (GPR), pulse-echo, infrared (IR) thermography and acoustic emission methods.

A more detailed description of the NDE techniques listed in table 2 along with examples of the available commercial equipment is provided in the IAEA-TCS-26 report. In addition to those listed in the table, other mechanical methods such as impulse response technique and spectral analysis of surface waves (SASW) are also noted as alternative methods for measurement of strength. Among all the NDE techniques, UT methods have the widest range of applications for the inspection of concrete structures. The most common techniques for inspection of concrete are based on the pulse velocity and the resonant frequency measurements. In addition to the dynamic elastic properties of the concrete, moisture content and the strength of concrete could also be evaluated by using the mathematical relationships between the damping constant and the physical properties of the object. Although some of these methods are currently considered as laboratory techniques, they have the potential to be adapted for field use in the near future.

Table 2. Common NDT techniques and applications for concrete structures (Ref.: IAEA–TCS–17)

	Application											
NDT Technique	Strength	Elastic Modulus	Thickness	Crack depth	Crack width	Crack distribution	Crack development	Honeycombing, voids	Lamination	Bar location	Bar size	Bar corrosion
Rebound hammer	X											
Penetration resistance	X											
Pull-out	X											
Ultrasonic	X	X	X	X				X	X	X		
Radar								X	X	X		
Infrared thermography						X		X	X			
Radiography			X					X		X	X	X
Acoustic emission							X					
Magnetic or eddy current										X	X	X
Half-cell Potential												X
Photography					X	X						

In addition to the more common half-cell potential electrical method, commercial instruments based on electrical resistivity, capacitance, and linear polarization are also being marketed for inspection of concrete structures. Commercial equipment using magnetic methods such as eddy current induction, flux leakage, and nuclear magnetic resonance (NMR) are available from a number of vendors. Significant advancements have been made in the area of electromagnetic testing methods (radio frequency and microwave). A large suite of short-pulse or GPR systems are now commercially available that allow rapid inspection of concrete structures. When measurements must be performed in a standoff manner, higher frequency microwave (MW) reflectometry and radar techniques have the potential to provide high resolution inspections for both material property and structural integrity (based on vibrometry techniques) assessments. Although promising, applications of MW techniques so far have been limited to small scale experiments.

Infrared (IR) thermography methods employing either focal plane array (FPA) or single active element scanner cameras are now being widely used for inspection of concrete structures. Significant improvements in this area could be made in the near future as the sensitivity of cooled IR cameras is rapidly improving. Alternative thermal imaging techniques such as pulsed thermography, vibro-thermography, and thermal tomography techniques are among a number promising techniques that could be adapted for inspection of concrete structure over large areas.[59,60]

Major advancements have been made over the past decade on the development portable and transportable radiography (X-ray sources and solid-state detectors) and radiometry (γ-ray) systems. These systems are expected to be more widely deployed in the future for inspection of civil engineering structures. Case studies on the application of portable linear accelerator systems that provide high-intensity X-rays have been reported for NDE of civil engineering structures.[61] These devices allow examination of structural members for hidden defects and general condition of large structures and components (over 16-in.-thick steel and 62-in.-thick concrete). Three representative case studies are discussed in detail, and new developments are highlighted, including use of robotics for positioning and the use of accelerators for curing composite materials in-situ. Rapid advancement of software-based tools for the analysis and visualization of data generated by high-resolution inspection techniques is expected to help significantly improve the effectiveness of NDE methods in the future. Availability of efficient computer tomography (CT) algorithms that would allow real-time processing of large amounts of data will help toward deployment of advanced NDE tools for field applications. Two main areas of application are for processing of data collected with X-ray and acoustic/ultrasonic based methods.

Numerous sensors and techniques have also been developed for monitoring the performance of civil engineering structures. They include embeddable and detachable sensors for measuring various indicators of structural integrity. Extensive studies are being conducted on the use of strain monitoring methods employing mechanical, electrical, and acoustic sensors. A number of improved AE techniques for detection of damage and degradation in concrete structures have been evaluated. In one study, a multi-

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[59] J. G. Sun, "Development of Nondestructive Evaluation Methods for Thermal Barrier Coatings," Proceedings of the 22nd Annual Conference on Fossil Energy Materials, July 2008.

[60] J. G. Sun, "Quantitative Three-Dimensional Imaging by Thermal Tomography Method," Rev. of Progress in QNDE: Vol. 30A, 30B, AIP, Vol. 1335, pp. 430-437, June 2011.

[61] R.D. Owen, "Portable Linear Accelerators for X-Ray and Electron-Beam Applications in Civil Engineering," *NDT&E International* **31**(6), pp. 401-409, December 1998.

sensor device comprising of a half cell potential, resistivity, eddy current, and chloride ion sensor was designed and tested.[62] The integrated device was fabricated and embedded into concrete slabs. Other multi-sensor devices have also been evaluated for OLM of corrosion and force for inner containment concrete structures. The probes used in one study included a half-cell potential sensor, a linear polarization resistance probe, an electrical resistance probe, and strain gauges.[63] Although OLM technologies are expected to play a major role in health monitoring of concrete structures for future reactor systems, applicability of the aforementioned technologies to the existing fleet of LWR plants has not been fully investigated. Future implementation of these technologies for field use will require new procedures, codes, and standards to be developed and qualified.

3.5 Detection of Leaks in Reactor Coolant Pressure Boundary

As noted previously, the primary focus of the scoping studies under Task 1 is on inspection and monitoring technologies for early detection of degradation in components before they lead to potential breaches in the pressure boundary. Nonetheless, a limited review of the available literature was conducted on the current and emerging technologies for detection of leaks from the reactor coolant pressure boundary (RCPB). Review of technologies for monitoring of leaks at NPPs in components external to structures is provided in connection with Task 4 studies.

Nuclear power plants in the past relied on sump pump water flow rate and visual inspections as their primary means of detecting leaks from the RCPB. This approach, while effective for detecting large leaks, was not effective for detecting and locating small leaks. Successful implementation of more robust mitigation strategies depends on the ability to detect leakages at an earlier stage and the ability to more precisely locate the affected zone. No single method (e.g., condensate flow monitors, sump monitors, primary coolant inventory balance, etc.) may provide optimal detection sensitivity and measurement accuracy in conjunction with accurate identification of leak location. On-line monitoring strategies that combine measurements from redundant sensor systems and alternate sensing modalities have the potential to improve the capability to detect and locate leaks at an earlier stage and with a higher degree of accuracy and reliability.

The ISA–67.03–1982 standard provides a summary of the existing methods and their capabilities for detecting, measuring, and locating leakage from the RCPB in LWRs.[64] As stated in that standard, detection of leakage from pressurized pipes and vessels is needed because small leaks may develop into larger leaks or ruptures and potentially result in the accidental loss of coolant during reactor operation. Remote leakage detection systems are necessary since the RCPB is housed in a containment structure and physical access is limited during power operation. The NRC Regulatory Guide (RG) 1.45 describes a number of approaches that are considered acceptable with regard to selecting reactor coolant leakage detection systems, monitoring for leakage, and responding to leakage in LWRs.[65] According to RG 1.45,

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[62] F. Lamonaca, A. Carrozzini, "Monitoring of Acoustic Emissions in Civil Engineering Structures by Using Time Frequency Representation," Sensors & Transducers Journal, Vol. 8, pp. 42-53, Feb. 2010.

[63] K. Kumar et al, Online Corrosion and Force Monitoring for Inner Containment Concrete Structures, Sensors & Transducers Journal, Vol. 92, Issue 5, pp. 108-121, May 2008.

[64] ISA-S67.03-1982, "Standard for Light-Water Reactor Coolant Pressure Boundary Leak Detection," 1982.

[65] Regulatory Guide 1.45, rev. 1 "Guidance on Monitoring and Responding to Reactor Coolant System Leakage," U.S. Nuclear Regulatory Commission, Washington, DC.

leakage monitoring strategy should include a combination of leakage monitoring instruments and methods. The process parameters to be monitored for detecting leaks include: level or flow rate to tanks and sumps; airborne particulate and gaseous radioactivity; containment atmosphere humidity, pressure and temperature; and condensate flow rate from air coolers. Examples that illustrate alternate monitoring methods for identifying the source of leakage are also provided in RG 1.45. Those methods include surface-mounted humidity sensors, AE sensors, and online surveillance with video cameras throughout the containment.

A database that identifies the leak source, leak rate, and the resulting actions from reactor coolant system (RCS) leaks discovered in U.S. LWRs is discussed in NUREG/CR-6861.[66] Information is provided about the source of leakage, the equipment that detected the leakage, and the method used to determine that the leakage was through the pressure boundary. The sensitivity, reliability, response time and accuracy of each type of leakage detection system are also evaluated. Although the focus of the report is on the existing technologies, new approaches such as infrared spectroscopy to the detection of leaks in the reactor head region by monitoring boric–acid aerosols are considered. Acoustic emission monitoring systems as a prospective tool for the detection of crack initiation and growth (i.e., before leaks occur) were also considered.

A review of the existing and emerging technologies for on-line detection of leakage in PWR primary coolant boundary is presented in EPRI TR-1012947.[67] Ongoing industry activities in this area are also discussed in that report. In addition to the primary on-line leak detection methods noted above, a number of enhanced on-line detection methods were also surveyed. They include local radiation, particle, moisture and humidity sensors. Local radiation detectors sense γ radiation emitted from gaseous Nitrogen 13 and Fluorine 18 in the primary coolant that would be released at the leak site. Highly sensitive N13-F18 detectors in operation can detect small leaks (<0.13 Gal/min) in the containment. Containment air particulate activity monitors measure the overall containment activity levels. Such systems can also be used to monitor specific areas of interest by local sampling (suction) and comparing the measurement with the background activity level. Humidity sensors (e.g., FLÜS system by Framatome ANP) can be installed inside the reactor containment and monitor leakage in NPP pressurized water or steam carrying components during plant operation. A number of fiber optic systems are also available for detection of gaseous substances including water vapor. The sensors operate based on the absorption of laser light tuned to the specific frequency of a gaseous substance of interest (e.g., water absorption). Local fiber optic sensors placed at strategic locations can provide information about the general area of a potential leaks. One limitation of the existing fiber optic sensors is the long-term degradation of their performance in high radiation environments. Acoustic emission sensors are also available for detection of leakage in RCPB. A typical AE system employs a number of sensors that measure high frequency sound waves in the region of interest. Triangulation of signals from multiple AE sensors is used to determine the approximate location of a potential leak. A survey of some prominent commercial AE systems from different vendors as well as field recent experience with AE systems is provided in EPRI TR-1012947. The use of AE equipment for both leak detection and for flaw detection and monitoring is discussed.

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[66] NUREG/CR-6861, "Barrier Integrity Research Program: Final Report," Kupperman, D. S., et al., prepared by Argonne National Laboratory for the U.S. Nuclear Regulatory Commission, Washington, DC, December 2004.

[67] *Materials Reliability Program: Survey of On-Line PWR Primary Coolant Leak Detection Technologies (MRP-187).* EPRI, Palo Alto, CA: 2005. 1012947.

Application of moisture-sensitive tapes for detecting and locating of leaks is also reviewed. Alternative techniques that measure the presence of Boron/Boric Acid deposits are also being investigated for detection of leakage. Prompt-gamma neutron activation analysis (PGNAA) is a promising technique that can be used to determine the presence and the amount of many elements. Systems are currently being developed for detection of Boron deposits under insulation. This NDE method, however, may only be applied during plant outages. Monitoring of Boron concentration in the containment air cooler condensate is noted as another potential indicator of leakage in RCPB. This method, however, does not provide information about the possible location of the leak within the containment. Finally, a survey is provided of the current state-of-the-art regarding remotely operated cameras and videoscopes for detecting leakage in RCPB. The key features and benefits of each system as well as recent field experience with radiation tolerant videoscopes are discussed.

In summary, the technology is available to improve leak detection capability at specified sites. More sensitive and quantitative techniques, however, may not always provide specific information about the location of a leak in the RCPB. The applicability and reliability of a number of promising leak detection and monitoring techniques needs to be further demonstrated. In general, leak detection techniques could be further improved in the following areas: (1) identifying leak sources through more precise location information and leak characterization, thus reducing the number false calls; (2) more accurate quantification of leak rates; and (3) implementation of integrated leak monitoring systems with alternate sensing modalities and increased sensitivity of individual sensor to help reduce the number of installed elements.

4. Review of Continuous On-line Monitoring Technologies

A limited survey of the available literature was performed on the existing and emerging technologies for real-time inspection and monitoring of material degradation. A number of more recent publications and reports on advances in on-line monitoring (OLM) systems were reviewed. Examples of conventional techniques for on-line condition monitoring of process parameters and components is provided in a 2008 IAEA report.[68] For long term predictive maintenance in NPPs the report suggests that trending (fault diagnosis) based either on empirical or physical models could help to more accurately predict the remaining useful life of components in comparison to conventional fault detection methods. Applicable condition monitoring techniques include those that employ microphones and accelerometer type sensors for vibration monitoring and for acoustic monitoring in its various forms (crack initiation and growth monitoring, acoustic leak detection, vibration monitoring, loose part monitoring, etc.). Other condition monitoring techniques include reactor noise analysis and motor electrical signature analysis. Reactor noise analysis is commonly based on data from such sensors as in-core flux/neutron detectors, ex-core ionization chambers, thermocouples, pressure and flow sensors, and ex-vessel accelerometers. Motor current signature analysis (MCSA) uses current sensors to monitor the change in input currents to electromechanical machinery to identify potential malfunctions. Hybrid condition monitoring technique (integration of two or more condition monitoring methods that combine physical and empirical modeling) is noted as a promising future trend in OLM technology for the nuclear power industry.

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[68] On-line Monitoring for Improving Performance of Nuclear Power Plants Part 2: Process and Component Condition Monitoring and Diagnostics, IAEA Nuclear Energy Series No. NP-T-1.2, 2008.

A summary of advances in instrumentation and controls (I&C) technology for selected applications to NPP upgrades and in new plants is provided in NUREG/CR-6992.[69] Sensors and measurement systems as well as surveillance, diagnostics, and prognostics are among the eight distinct I&C technology focus areas identified in that report. The key regulatory issues of concern include sensor response time requirements; accuracy of the instrumentation, sensor drift (need for improved stability to minimize calibration requirements), and qualification issues associated with new sensor technologies. As noted in a number of similar reports on OLM technologies, the principal variables measured for safety-related applications continue to be neutron flux, temperature, pressure, radiation, flow, position, and level. Emerging sensor technologies reviewed in that report include 1) distributed fiber-optic-based Bragg grating thermometry for health monitoring of electromechanical components, 2) Ultrasonic technologies (wireline pulse-echo sensor for temperature measurement) for future in-vessel deployment, 3) Johnson noise thermometry (JNT) for temperature measurement, 4) Gamma thermometers for long-term baseline power measurement in boiling-water reactor (BWR) cores, and 5) Type-N thermocouples (as a more stable replacement for the widely deployed Type-K). Many of these sensor technologies, although developed many years ago, have not been widely deployed in the nuclear power plants in the U.S. Among the sensors listed above, Johnson noise thermometer was identified as the only technology that could potentially eliminate the need for manual calibration. The promising technologies identified in that report are also applicable primarily to OLM of active components.

4.1 OLM techniques for SCC Initiation and Growth

A number of publications and reports have also been reviewed in connection with possible in-situ detection and monitoring of stress corrosion cracking (SCC) initiation and growth in LWRs. The IAEA-TECDOC-1303 report provides the results of the Coordinated Research Project (CRP) on high-temperature (HT) on-line monitoring of water chemistry and corrosion in PWRs, BWRs and in research reactors.[70] The report presents an overview of the state-of-the-art with regard to OLM of water chemistry and corrosion in operating reactors and on the development and qualification of promising monitoring techniques. In-situ HT measurements—without changing the physical and chemical state of the reactor water—can potentially overcome known disadvantages associated with conventional sampling procedures. The results of laboratory and field experiments by a number of international participants on the application of electrochemical corrosion potential (ECP), electric current noise (ECN), electrochemical noise (EN), and electric potential Noise (EPN) is presented. Although no clear consensus is provided on the status of the technology, some general remarks are made regarding future directions in HT OLM of water chemistry and corrosion. High-temperature OLM is needed primarily for secondary side measurements in PWRs. Despite their long history, ECP measurements used for such applications have not attained a widespread use. Also, it is not yet clear whether direct measurement of corrosion phenomena (corrosion rate, oxide-film characteristics, cracking susceptibility, etc.) will lead to plant implementation. Monitoring the behavior of SCC in pressure-retaining and reactor-internal components in BWRs has been studied extensively using ECP measurements. No method is currently available for OLM of crack initiation through SCC. Various methods for in-situ determination of the tendency for

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[69] Instrumentation and Controls in Nuclear Power Plants: An Emerging Technologies Update, NUREG/CR-6992, U.S. Nuclear Regulatory Commission, Washington D.C. 2009.

[70] High temperature on-line monitoring of water chemistry and corrosion control in water cooled power reactors, Report of a coordinated research project 1995–1999*,* IAEA-TECDOC-1303, July 2002.

crack growth have been used in commercial reactors both in recirculation piping and side-stream autoclaves and in-core to monitor irradiation assisted stress corrosion cracking (IASCC). Such crack-growth monitors are able to provide valuable real-time information. Optical methods and advanced electrochemical techniques (thin-film, contact electrical resistance, EN, etc.) are proving very useful for mechanistic studies. Further development of these sensor technologies, however, is required before they can be considered for field use. In-core crack-growth-rate measurements are in use for IASCC studies at various test reactors and have also been performed in commercial plants, but they cannot yet be regarded as a routine monitoring tool. In-situ monitoring can provide new and valuable information to plant operators. As stated in the report, full benefit from using OLM sensors will only be obtained if the data can be processed in real time using computer-aided diagnosis systems.

4.2 Acoustic Emission Monitoring

The ability of AE to detect the energy release of a flaw which undergoes an evolution produced by a given stress enables one to acquire accurate measurement on crack initiation, growth, onset of new defects and their dynamic behavior, during the first hydrotest and later requalification testing of nuclear components and for continuous monitoring during power plant operation. The AE technique is able to provide useful information for the diagnosis and prognosis of degradation phenomena in progress. As AE is a narrow-band passive sensing method, its applicability depends on the physics of damage propagation. It is generally considered as a mature technology with a wide range of industry quality hardware and software available for different applications (see Fig. 17). The technique has also been used extensively for detection of leaks from pressurized vessels.

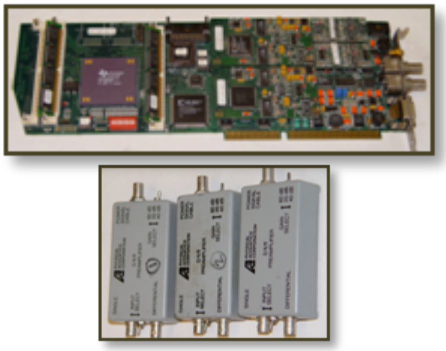

Figure 17. A general purpose commercial AE board (top) and the associated high-gain amplifiers (bottom) from Physical Acoustics Co. [*courtesy of ANL*].

A wide range of acoustic monitoring techniques have been employed for on-line monitoring of NPP components.[71],[72],[73],[74],[75],[76],[77] Applications include crack initiation and growth monitoring, acoustic

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[71] McElroy J. W., “Topical Report, Acoustic Emission Crack Detection Methods for Light Water Reactor Application” DOE Report C0035208-4, Philadelphia, Pennsylvania, 1982.

[72] Hutton, P.H., Kurtz, R. J., Pappas R. A., Dawson J. F., Dake L. S., Skorpik J. R., “Acoustic Emission Results Obtained from Testing the ZB-1 Intermediate Scale Pressure Vessel- An Interim Report” NUREG/CR-5144, PNL-6549, U.S. Nuclear Regulatory Commission, Washington D.C. 1985

[73] Kupperman D. S., Prine D., Mathieson T., “Application of Acoustic Leak Detection technology for the Detection and Location of Leaks in Light Water Reactors,”NUREG/CR-5134, U.S. Nuclear Regulatory Commission, Washington, D.C. 1988.

[74] Hutton, P.H., Kurtz, R. J., Friesel M. A., Skorpik J. R., Dawson J. F., Acoustic Emission /Flaw Relationships for In-Service Monitoring of LWRs” NUREG/CR-5645, PNL-7479, U.S. Nuclear Regulatory Commission, Washington D.C. 1991.

[75] Kupperman, D.S., Sheen S.H., Shack W.J., Dierks D.R., Krishnaswamy P., Rudland D. Wilkowski G.M., “Barrier Integrity Research program: Final Report” NUREG/CR-6861, U.S. Nuclear Regulatory Commission, Washington D.C., 2004.

leak detection, vibration monitoring, and loose part monitoring. A recent review paper provides a history of past applications of AE technology and future directions for successful deployment of this technology for field use.[78] The design of a proper performance demonstration program for AE is pointed out as one of the main challenges to successful widespread deployment of this technology.

4.3 Active Sensing Technique

Limited scoping studies were also conducted on emerging technologies for on-line structural health monitoring and condition based damage state forecasting. Research performed at Argonne and at other institutions on crosscutting OLM methods for existing and new reactor vessels and for other safety critical structures are currently being reviewed.[79,80] Real-time or on-line structural health monitoring technologies are expected to play an increasingly greater role in the nuclear power industry because of a) more stringent safety requirements for critical structures, b) the need to reduce the cost of periodic inspections and maintenance, and c) advancements in distributed sensor technologies and on-board signal processing and data analysis capability.

In an online structural health monitoring approach the overall structure to be interrogated can be divided into multiple safety critical zones. A critical zone is defined as the zone or area in which some unwanted events (e.g., structural damage) is initiated and the growth of which could eventually undermine the overall structural integrity of the system. For example, the welding area in a reactor pressure vessel can be an example of a critical zone. In an online monitoring approach each critical area to be monitored by a group of permanently bonded sensors of same or different kind. Each group of sensors can be referred as a sensor node. To monitor the overall structure depending on the number of critical zones multiple numbers of such sensor nodes can be permanently bonded to the structure. The sensor nodes all together can be referred as sensor network. An unanticipated loading and changes in environmental condition can lead to unanticipated damage state in a system. The goal of the on-line damage estimator is to determine the state of the structure at a particular structural hot spot monitored by a particular sensor node. A particular sensor node can include single or multiple sensors of the same or of different type. For example to monitor a weld zone both active and passive sensors can be used. The passive sensors such as bonded foil strain gauges (e.g., resistive, capacitive, fiber optic) and thermocouples can be used for monitoring of mechanical and temperature load. A current state estimator

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[76] Jirapong Lim, Tonphong Kaewkongka, "Micro Cracking in Stainless Steel pipe Detection by using Acoustic Emission and Crest Factor technique" Instrumentation and Measurement Technology Conference - IMTC 2007 Warsaw, Poland, May 1-3, 2007.

[77] R. Ricardo da Silva, D. Mery, S. D. Soares, "Evaluation of Acoustic Emission Signal Parameters for Identifying the Propagation of Discontinuities in Pressure Vessel Tubes" Materials Evaluation Volume 66 Number 5 pp. 493-500, May 2008.

[78] S. E. Cumblidge, S. R. Doctor, L. J. Bond, T. T. Taylor, T. R. Lupold, A. B. Hull, and S. N. Malik, "Analysis of Emerging NDE Techniques- Methods for Evaluating and Implementing Continuous Online Monitoring," Proceedings of ICONE17, 2009.

[79] Mohanty, S., Chattopadhyay, A., Wei, J and Peralta, P., "Real time Damage State Estimation and Condition Based Residual Useful Life Estimation of a Metallic Specimen under Biaxial Loading", 2009, *Structural Durability & Health Monitoring Journal,* vol.5, no.1, pp.33-55.

[80] Mohanty, S., Chattopadhyay, A., Wei, J and Peralta, P., "Unsupervised Time-Series Damage State Estimation of Complex Structure Using Ultrasound Broadband Based Active Sensing", 2010, *Structural Durability & Health Monitoring Journal,* vol.130, no.1, pp.101-124.

algorithm can run in a local micro-processor attached to the sensor node or can run in a remotely placed computer with the sensor data transmitted via a wireless network.

Analogous to the passive sensing approach, active sensing can be employed for online estimation of damage states. Unlike passive sensing, the active sensing approach use an actuation device (transducer) bonded to the structure (see Fig. 18). These devices transmit predetermined narrow or broadband signals to the structure that is being interrogated. The corresponding sensor signals are acquired and used for estimation of the damage state. The detection and quantification capability of an active sensing system depends on the frequency band of the input signal. For example, high frequency ultrasonic and electromagnetic excitation signals could be used for detecting small defects or damage at an early stage. The current states information at a typical sensor node can be fed to an online predictor to forecast the future state of the structure. The predictor algorithm has to work in real-time. Nonlinear pattern reorganization techniques can be used to forecast the future damage states based on the current estimated states. The results of studies to date suggest that nonlinear pattern recognition in conjunction with machine learning approach could be used to identify complex fault trends and to further help more accurately forecast such events. The emergence of reconfigurable "smart sensors" that measure, process, self-calibrate, and wirelessly transmit (RF/microwave transmission bands) information is expected to significantly improve the ability to monitor the condition of critical components and structures in many industries. Integrated sensing systems are being developed and marketed for monitoring a wide range of physical and process parameters. Adaptation of smart sensor networks to structural health monitoring in the nuclear power industry is an active area of multidisciplinary research and development. Extensive performance demonstrations must be conducted and new codes and regulatory guidelines need to be developed before any such new technology gains widespread acceptability for monitoring of SSCs in the nuclear power industry.

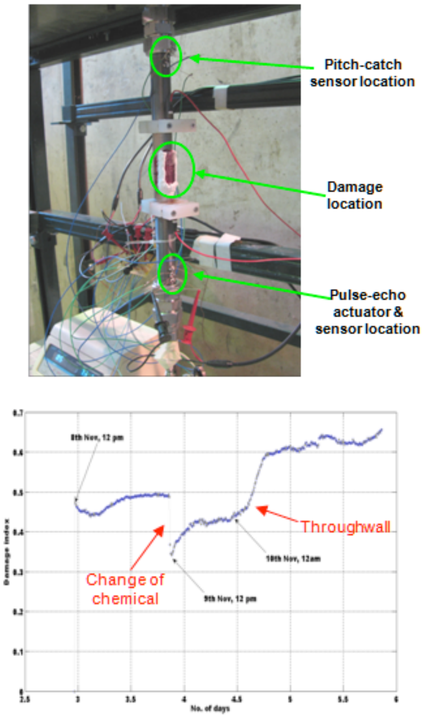

Figure 18. (Top) Active sensing setup for crack initiation and growth measurements. (Bottom) Events recorded over a six-day period (*Argonne National Laboratory*).

4.3 Fleet-wide OLM

A summary of the past and planned research activities in the area of empirical model-based on-line monitoring (OLM) and equipment condition assessment (ECA) is provided in EPRI TR-1010266.[81] Efforts on the development of ECA systems in application to implementation of a fleetwide monitoring (FWM) center are discussed in that report. FWM is considered as the most comprehensive approach to monitoring programs which may be implemented at any level (individual component, plantwide, or fleetwide). The report points to the significant efforts required to enable prognostic assessments from

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[81] *Fleetwide Monitoring for Equipment Condition Assessment.* EPRI, Palo Alto, CA: 2006. 1010266.

commonly deployed advanced monitoring applications. This includes development of interpretative schemes for processing of cumulative knowledge from multiple monitoring applications. The report also outlines the technology and implementation gaps for a centralized FWM facility. Some of the main challenges of FWM include standardization, cost justification, centralization of management, sensor alarm management, and technology integration.

Advanced OLM systems such as that developed originally at Argonne are commercially available.[82] However, a number of issues must be addressed before the full potential of an FWM facility deploying multiple advanced monitoring applications can be realized for power plant applications.[59] Conventional ECA systems are primarily sensor validation tools with the added capability to interpret anomalous signals (deviations from normal behavior of measured process variables). The use of ECA systems as a prognostic tool requires employment of predictive algorithms for interpretation of a large number of possible failure signatures. Potential technology gaps for implementation of FWM are also listed in EPRI TR-1010266 which includes sensor technologies (e.g., wireless) with enhanced capabilities, development of meaningful prognostic failure signatures, and automation of ECA alarm parameters. An example is provided in that report on how the combination of two new technologies (equipment predictive monitoring software and wireless vibration sensors) could help detect failures at an earlier stage than conventional vibration analysis alone.[83] Adaptation of sensors with wireless communication is proposed as a viable approach to implementation of ECA systems with improved diagnostic capability. Wireless technology is expected to gain more widespread use for future OLM applications. More sophisticated onboard processing capability of smart sensors can further help implement more robust ECA models. Accordingly, efficient wireless data transmission protocols need to be developed to handle a large number of distributed sensor nodes that monitor various aspects of plant operations.

4.4 Wireless Sensor Technology

Limited scoping studies were also conducted on advanced sensor technologies for OLM applications. Literature search in this area focused primarily on wireless sensor networks (WSNs), which can be described as integration of sensors with embedded processing capability and wireless communication using an ad hoc networking protocol. In theory, any number of different sensing elements (acoustic, electromagnetic, radiation, etc.) may be used for measuring process parameters. Each node (smart sensor) in a distributed network independently collects and processes data. The information is then transmitted to another node, a gateway, or the base station for further processing. Other features of advanced sensor networks include their self-healing (compensating for faulty sensors by routing the information through other nodes) and energy harvesting (use of ambient or process generated energy to prolong the lifetime of battery powered nodes) capabilities. Several embedded operating systems (e.g., IEEE 802.15.4, ZigBee, TinyOS) have been developed for different software platforms to render optimal exploitation the memory limits of WSNs.

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[82] *On-Line Predictive Condition Monitoring System for Coal Pulverizers: Application of Wireless Technology.* EPRI, Palo Alto, CA; SmartSignal Corp., Lisle, IL; and Dynegy Midwest Generation, Decatur, IL: 2003. 1004902.

[83] *Demonstration of Wireless Technology for Equipment Condition Assessment: Application at TXU Comanche Peak Steam Electric Station. EPRI, Palo Alto, CA: 2005. 1011826.*

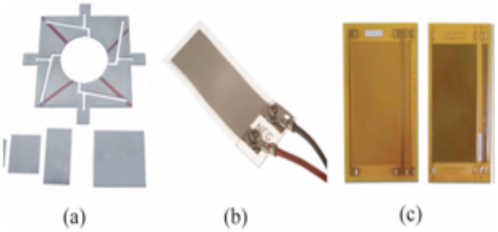

Figure 19. (a) PZT, (b) PVDF, and (c) MFC piezoelectric sensors. (*Yun et al*)

A general assessment of the current and emerging trends in smart/intelligent sensor technologies is provided by *Yurish*.[84] Distinction is made between "smart sensor"—a combination of a sensor, an analog interface circuit, an analog to digital converter (ADC) and a bus interface in one housing— and "intelligent sensor"— a smart sensor with one or several intelligent functions (such as self-testing, self-identification, self-validation, self-calibration, self-compensation, self-adaptation, etc.). In addition to smart sensors, it is predicted that sensors based on micro-electromechanical system (MEMS) will gain more widespread use because the technology offers the potential to develop highly miniaturized and cost-effective devices. The importance of advanced packaging technologies—System-in-Package (SiP) vs. System-on-Chip (SoC)—is also noted as an important factor in developing more functionally flexible smart sensor systems. A detailed survey of WSN technology for various applications is presented by *Akyildiz et al*. [85] Factors influencing the design of a network are also described. The main factors include fault tolerance, scalability, production costs, operating environment, sensor network topology, hardware constraints, transmission media, and power consumption.

Figure 20. Some wireless smart sensor prototypes (*Cho et al.,2008*)

A large body of literature exits on the topic of WSNs based on smart sensor technology (see Fig. 20). Majority of research activities in this area are associated with the wireless networking and data interpretation aspects of such systems with less emphasis placed on the sensor technology. Selected examples on the use of sensor networks for continuous monitoring of passive components and structures are presented next. Application of a WSN coupled with accelerometer sensors for non-invasive monitoring of flow rate and other flow patterns in pipeline networks is presented in *Awawdeh et al*. [86] The sensors track flow-induced vibrations to directly estimate the change in the flow rate, which may be used as an early warning of integrity loss in pipelines. WSN systems with on-board off-the-shelf acoustic, vibration, and temperature sensors have also been used in the past to detect degradation such as wall thinning in pipes through temperature or noise measurements and to detect leakage through real-time analysis of flow and pressure measurements. Implementation of an integrated system for a scalable WSN for structural health monitoring is reported by *Pakzad et al*. [87] Bidirectional accelerometer sensor nodes and a WSN with TinyOS operating system was developed for

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[84] S. Y. Yurish, *Sensors: Smart vs. Intelligent*; Sensors & Transducers Journal, Vol.114, Issue 3, March 2010, pp. I-VI.

[85] I.F. Akyildiz et al, *Wireless sensor networks: a survey*, Computer Networks 38 (2002) 393–422.

[86] A. Awawdeh et al, *Wireless Sensing of Flow-Induced Vibrations for Pipeline Integrity Monitoring,* Fourth IEEE Workshop on Sensor Array and Multichannel Processing, 2006.

[87] S. N. Pakzad et al, *Design and Implementation of Scalable Wireless Sensor Network for Structural Monitoring*, Journal of Infrastructure Systems, Vol. 14, No. 1, March 1, 2008.

monitoring and identification of different vibration modes. The use of MOTEs (wireless transceiver in conjunction with sensors) for environmental monitoring applications has also been reported by a number of authors. A WSN for monitoring of radiation levels around and inside a nuclear power plant is by *Barbaran et al.*[88] The system consists of wireless radiation sensor nodes at fixed positions throughout the plant and at mobile nodes (staff equipped with radiation monitoring and mobile devices (PDAs)) to monitor conditions around the plant.

A review of new trends in MEMS-based sensor technology is reported by *Nieva*.[89] Sensor systems based on micro/nano electromechanical systems (MEMS/NEMS) and micro-opto mechanical systems (MOEMS) that can operate in the presence of high temperatures, corrosive media, and/or high radiation hold great promise for harsh environment applications. The main advantage of silicon-based MEM/NEM technology is the possibility of integration with microelectronics, thus allowing miniaturization of devices. Silicon carbide (SiC) based devices have been manufactured for pressure, force, and acceleration sensing. Capacitive-based sensors have also been used to measure pressure, force, acceleration, and flow rate at high temperatures. Optical MEMS sensors can be developed to measure displacement, pressure, temperature and stress and are particularly suitable for liquid and gas measurements. The sensors are highly resistant to electromagnetic and radio frequency interference (EMI and RFI) and eliminate the need for onboard electronics.

Fiber-optic MEMS are robust, highly resistant to EMI and RFI, and can potentially detect displacements on a sub-nanometer scale. However, their performance depends on mechanical–thermal noise, photodetector noise, fabrication imperfections, and assembly. Fabry-Perot MOEMS sensors fabricated with SiC materials can provide better functionality (reliability and sensitivity) compared to classical fiber-optic sensors, and are ideal for the manufacturing of low-cost on-chip smart systems. A new type of multifunctional composite based on multi-walled carbon nanotubes (MWCNT) is reported by *Li et al.*[90] This new type of carbon nanotube-based composite can potentially serve as both a strain gauge and as a damping treatment in structural vibration control. Development of flexible all-organic bi-layer film-based sensors capable of measuring strain in a wide range of elongations and temperatures is reported by *Laukhina et al.*[91] These sensors could potentially provide low-cost replacements to conventional metal-based strain and pressure gages for various monitoring applications. Development of a polymer-based (PVDF) micromachined acoustic emission (AE) sensor is reported by *Feng et al.*[92] PVDF is a highly non-reactive and flexible material which would allow AE sensing elements to be attached directly to a curved surface.

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[88] J. Barbaran et al, *RadMote: A Mobile Framework for Radiation Monitoring in Nuclear Power Plants*, International Journal of Electrical and Computer Engineering 2:10 2007.

[89] P. M. Nieva, *New Trends on MEMS Sensor Technology for Harsh Environment Applications*, Sensors & Transducers Journal, Special Issue, October 2007, pp. 10-20.

[90] X. Li and C. Levy, *A Novel Strain Gauge with Damping Capability***,** Sensors & Transducers Journal, Vol. 7, Special Issue, October 2009, pp. 5-14.

[91] E. Laukhina et al, *Film-based Sensors with Piezoresistive Molecular Conductors as Active Components: Strain Damage and Thermal Regeneration*, Sensors & Transducers Journal, Vol. 10, Special Issue, February 2011, pp. 1-12.

[92] G-H Feng and M-Y Tsai, *Acoustic emission sensor with structure-enhanced sensing mechanism based on micro-embossed piezoelectric polymer*, Sensors and Actuators A 162 (2010) 100–106.

An overview of more recent applied research activities on smart sensing, monitoring, and damage detection for civil infrastructures are provided in a number of recent publications.[93],[94] These articles discuss the state-of-the-art in smart sensors technology including optical fiber sensors, piezoelectric sensors, and wireless sensors. A brief overview is also provided of the recent advances in the structural monitoring techniques such as ambient vibration-based bridge health evaluation, piezoelectric sensors-based local damage detection, wireless sensor networks and energy harvesting (see Fig. 21), and wireless power transmission by laser/optoelectronic devices.[95] A more detailed review of WS technology is provided in connection with Task 2 activities under this project.

Figure 21. Vibration energy harvesting for wireless sensors by KCF Technologies. [*https://www1.eere.energy.gov/manufacturing/industries_technologies/sensors_automation/pdfs/kcf_vibrationpower.pdf*]

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[93] C-B Yun and J Min, "Smart Sensing, Monitoring, and Damage Detection for Civil Infrastructures," KSCE Journal of Civil Engineering (2011) 15(1):1-14.

[94] Cho, S., Yun, C-B., Lynch, J. P., Zimmerman, A. T., Spencer, B. F., and Nagayama, T.. "Smart wireless sensor technology for structural health monitoring of civil structures." *Int. J. Steel Struct.*, Vol. 8, pp. 267-275, 2008.

[95] S. A. Jang, "Structural Health Monitoring for Bridge Structures using Wireless Smart Sensors," Dissertation, 2010.

4. Summary and Conclusions

A review of the available literature was carried out with the goal of identifying the emerging trends and potential technology gaps in sensors and techniques in application to in-situ inspection and monitoring of material degradation in nuclear power plant structures, systems, and components (SSCs). The focus of this scoping study was mainly on promising technologies for early detection and characterization of degradation in susceptible materials and components. To help narrow down the scope of studies on this rather broad topic, the review was limited mostly to the emerging technologies for detection of damage and degradation in passive components, which inherently pose a greater challenge to nondestructive examination (NDE) and on-line monitoring (OLM) methods. To that end, emerging inspection and monitoring techniques for plant life extension were reviewed. To a lesser extent, advanced technologies for specialized and new applications were also reviewed. Little emphasis was placed on conventional sensors used for OLM of basic process parameters (i.e., temperature, pressure, level, flow, vibration, leak, valve position, radiation/flux, coolant chemistry, etc.).

A number of emerging NDE techniques that could potentially provide more efficient and reliable inspection and monitoring capabilities have been identified. A non-exhaustive review of the available literature was made on the application of these technologies particularly with regard to corrosion, corrosion-cracking, fatigue, creep, metallic diffusion, and in susceptible materials and components such as similar/dissimilar metal welds, vessel claddings, and concrete. Some promising active and passive sensing technologies that could potentially allow in-situ monitoring of crack initiation and growth have also been noted. Literature review was also conducted of the existing and emerging NDE and OLM techniques in application to some specific areas of interest to this scoping study. The SSCs of particular interest included buried components and concrete structures in NPPs. A number of promising NDE techniques for inspection of buried piping that require either excavation or entry methods (e.g., VT, GW-UT, PEC) and those deployed using pigs (PEC, RFECT, MFL, UT, and laser-UT) were noted. For inspection of concrete structures, in view of their application, both common NDE techniques (e.g., rebound hammer, penetration resistance, AE, VT, RT, GPR, photography, half-cell potential) and emerging techniques (e.g., enhanced VT, IR thermography, SASW, NMR, RT, UT) were noted. Additionally, a review was conducted of the existing and emerging technologies for detection of leaks in reactor coolant pressure boundary (RCPB). Some general suggestions were made in connection with improving the reliability of existing leak detection techniques. The current state-of-the art with regard to measurement of residual stress (RS) in components was also reviewed. Both conventional and promising emerging techniques (compact XRD, laser shearography, and UT method based on L_{CR} waves) were discussed.

More prominent emerging NDE technologies, in their various forms, that can be employed for in-situ inspection of NPP components include enhanced ECT, UT, VT, and RT methods. Eddy current testing with high resolution arrays of thin-film and solid-state elements are being evaluated for a number of inspection and monitoring applications. For examination of electrically thick components, in addition to conventional remote field and pulsed ECT methods, specialized deep-penetrating probes with inductive and magneto-resistive elements have the potential to provide improved detection sensitivity in comparison to conventional eddy current techniques. For detecting deeply embedded flaws, the emerging SQUID technology can provide superior sensitivity to conventional induction sensing techniques.

Magneto-optic imaging systems also hold promise for real-time visualization of eddy current distribution over relatively large areas.

A number of versatile UT techniques have been developed in recent years. Modern UT instruments employing phased array technology are evolving rapidly and are expected to be more widely deployed in the future for field applications. Newly developed UT methods based on TOFD, long-range guided waves, laser excitation and detection, nonlinear ultrasonics, and EMAT technology are being evaluated for a wide range of NDE applications including for inspection of SSCs in nuclear power plants. Both laser UT and EMAT are non-contact techniques (i.e., eliminate the need for couplants used in conventional UT) that inherently allows for more rapid examinations. The non-contact nature of these methods is of particular significance as it overcomes a major limitation of traditional UT with piezoelectric transducers. These methods further allow measurements to be made under adverse test conditions (e.g., parts at elevated temperatures and in corrosive environments) for which the use of contact type probes may be impractical. Assessments to date suggest that phased array EMAT technology could offer certain advantages over conventional UT for examining coarse grain materials (e.g., cast stainless steel components) and for inspection of SSCs with non-ideal surface conditions including parts with coating and cladding. Further confirmatory studies, however, are needed to reliably demonstrate the performance of emerging UT techniques for routine field use.

Several other emerging and newly developed NDE methods with potential application to in-situ inspection and monitoring of SSCs in nuclear power plants have also been noted in this report. They include enhanced VT systems with miniature video cameras and advanced image processing and visualization tools, optical methods based on fiber optic sensors and digital speckle correlation technique, radiographic and diffraction methods with portable X-ray instruments, IR thermal imaging including vibrothermography and thermal tomography, and RF and microwave techniques. Some of the aforementioned technologies are expected to play a more prominent role for NDE of advanced reactor systems that employ ceramic and composite materials for high temperature applications. Promising in-situ NDE methods using active and passive distributed sensor elements (capacitive, inductive, fiber optic, acoustic, and strain gauges) have also been noted in this report. Significant level of research and development is currently being carried out in this area. A wide suite of sensors and techniques have been developed for applications in automotive, aerospace, and construction industries. Applicability of the emerging sensor systems to the inspection and monitoring of NPP components remains to be demonstrated.

In general, common features of modern NDE equipment include: higher degree of inspection automation (hardware and software); faster inspections through employment of linear and matrix array sensor configurations; increased accuracy and quantification capability; greater penetration depth and higher spatial resolution; more flexible and modular tools allowing incorporation of multiple sensors in the probe assembly; compact systems (integrated inspection units for rapid deployment); rugged probes for operation in harsh environments (elevated temperature and pressure, radiation, moisture, and corrosive media); inspection techniques that are less affected by the surface condition of components.

Traditional analog systems for sensing basic process parameters in NPP operation have limitations with respect to accuracy, ease of maintenance and data quality. To reduce the costs and improve performance of NPPs digital systems are being applied as replacements in the nuclear industry. A wide range of sensors are currently available for measuring basic process parameters and for monitoring of degradation in active components and plant instrumentation. In addition to conventional sensors (e.g., thermocouples, resistance temperature detectors, differential pressure sensors, etc.) a number of new industrial grade sensors (e.g., fiber optic, ultrasonic, resistive, capacitive, inductive, etc.) are now commercially available. Examples of emerging sensor technologies include distributed fiber-optic-based Bragg grating thermometry for health monitoring of electromechanical components, ultrasonic wireline pulse-echo sensor for temperature measurement for future in-vessel deployment, Johnson noise thermometry for calibration-independent temperature measurement, Gamma thermometers for long-term baseline power measurement in BWR cores, and Type-N thermocouples. Review of the open literature generally suggests that there are currently no major technology gaps with regard to sensors for measuring basic process parameters and for monitoring of active components. Efforts, however, are needed toward development of procedures for adapting and ultimately deploying the existing sensors and prototypes devices for NPP applications. This process will inherently require involvement by utilities, professional committees (IEEE, ISA, ASTM, etc.) as well as the regulatory organizations.

Existing OLM systems operate primarily as fault-detection systems. They are used to monitor instrument channel performance and as sensor validation tools. A number of projects are currently being sponsored by utilities and federal agencies to develop advanced OLM systems for diagnostics and prognostics that not only detect but also forecast the health of operating machinery. While significant progress has been made in that area, advanced OLM systems have not yet been widely deployed for use in the existing fleet of reactors. This trend seems to be changing as the technology becomes more mature and proper performance demonstration and qualification procedures are put in place. It is worth noting once again that while the emerging OLM systems that utilize the available information from the existing plant sensors are expected to improve the reliability in monitoring of active components, health monitoring of passive components remains to be a challenge in the foreseeable future. New sensor technologies and specialized in-situ NDE techniques thus need to be developed in parallel in order to take full advantage of the cost benefit potential of modern OLM systems.

A number of recent publications were referenced in this report in connection with advances in I&C technology for selected applications to NPP upgrades and in new plants. The emerging trends in sensors and measurement systems as well as surveillance, diagnostics, and prognostics methods were discussed. In general, the principal variables measured for safety-related applications continue to be neutron flux, temperature, pressure, radiation, flow, position, and level. Many of these sensor technologies, although developed many years ago, have not been widely deployed in the nuclear power plants in the U.S. As noted earlier, promising OLM technologies identified in a number of recent reports on I&C technology are applicable primarily to monitoring of active plant components.

For long term predictive maintenance in NPPs trending (fault diagnosis) based either on empirical or physical models has the potential to more accurately predict the remaining useful life of components in comparison to conventional fault detection methods. Applicable condition monitoring techniques include those that employ microphones and accelerometer type sensors for vibration monitoring and for acoustic monitoring in its various forms (crack initiation and growth monitoring, acoustic leak detection, vibration monitoring, loose part monitoring, etc.). Other condition monitoring techniques include reactor noise analysis and motor electrical signature analysis. Hybrid condition monitoring technique (integration of two or more condition monitoring methods that combine physical and empirical modeling) is noted as a promising future trend in OLM technology for the nuclear power industry. The reliability of emerging OLM techniques, however, for early detection of material degradation in passive components and prediction of their remaining useful life needs to be further evaluated.

A number of publications and reports have also been reviewed in connection with possible in-situ detection and monitoring of SCC initiation and growth in LWRs based on coolant chemistry. The reports provide an overview of the state-of-the-art in connection with OLM of water chemistry and corrosion in operating reactors and on the development and qualification of promising monitoring techniques. In-situ high temperature measurements can potentially overcome known disadvantages associated with conventional sampling procedures. The results of laboratory and field experiments on the application of ECP, ECN, EN, and EPN were discussed. In general, high-temperature OLM is needed primarily for secondary side measurements in PWRs. Despite their long history the techniques used for monitoring of SCC have not attained widespread use. Also, it is not yet clear whether direct measurement of corrosion phenomena (corrosion rate, oxide-film characteristics, cracking susceptibility, etc.) will lead to plant implementation. Monitoring the behavior of SCC in pressure-retaining and reactor-internal components in BWRs has been studied extensively. No method is currently available for OLM of crack initiation through SCC. Various methods for in-situ determination of the tendency for crack growth have been used in commercial reactors both in recirculation piping and side-stream autoclaves and in-core to monitor IASCC. Such crack-growth monitors are able to provide valuable real-time information. Optical methods and advanced electrochemical techniques (thin-film, contact electrical resistance, EN, etc.) are proving very useful for mechanistic studies. Further development of these sensor technologies, however, is required before they can be considered for field deployment. In-core crack-growth-rate measurements are in use for IASCC studies at various test reactors and have also been performed in commercial plants, but they cannot yet be regarded as a routine monitoring tool. In-situ monitoring can provide new and valuable information to plant operators, however, full benefit from using OLM sensors will only be obtained if the data can be processed in real time using computer-aided diagnosis systems.

Limited scoping studies were also conducted on emerging technologies for on-line structural health monitoring and condition based damage state forecasting. Real-time or online structural health monitoring techniques using passive and active distributed sensors are expected to play an increasingly greater role in the nuclear power industry. Analogous to the passive sensing approach such as AE, active sensing can be employed for online estimation of damage states. Nonlinear pattern reorganization techniques can be used to forecast the future damage states based on the current estimated states. The results of studies to date suggest that nonlinear pattern recognition in conjunction with machine learning algorithms could provide the means to identify complex fault trends and to further help forecast potential events at an earlier stage. Integrated sensing systems are being developed and marketed for monitoring a wide range of physical and process parameters. Adaptation of smart sensor networks to structural health monitoring in the nuclear power industry is an active area of multidisciplinary research and development. Extensive performance demonstrations must be conducted and new codes and regulatory guidelines need to be developed before any such new technology gains widespread acceptability for monitoring of SSCs in the nuclear power industry.

A limited scoping study was also conducted on advanced sensor technologies. A review was provided of “smart” and “intelligent” sensors with potential applications to monitoring of material degradation in NPPs. Smart and intelligent sensors in the future are expected to be used for monitoring of both internal and external stressors and to further provide self-diagnostics capability. Energy-efficient sensors based on MEMS with embedded artificial intelligence capability are being developed. Application of these advanced sensor technologies to monitoring of SSCs in nuclear plants will be the topic of future research activities. A large body of literature also exits on the topic of WSNs that employ distributed networks of smart sensors. Majority of research activities in this area are associated with the wireless networking and data interpretation aspects of such systems with less emphasis placed on the sensor technology itself. A more detailed review of WSN technology is provided in connection with Task 2 and Task 3 scoping studies under this project.

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