2015

Needs and opportunities: nondestructive evaluation for energy systems

Leonard J. Bond
Iowa State University, bondlj@iastate.edu

Needs and opportunities: nondestructive evaluation for energy systems

Abstract
Advanced manufacturing and new energy systems are presenting a wide variety of challenges for nondestructive testing and evaluation (NDT/NDE). This paper discusses the state of the art, needs and opportunities for NDE to provide reliable, effective and economic inspection and monitoring for energy systems. It introduces issues of materials, defects and allowables, the evolution of advanced NDT and NDE and then considers examples of NDE for energy systems. These include applications in the petrochemical industry, advanced and additive manufacturing, solar cells, wind turbines, nuclear systems and some underlying issues of large scale composites, pipes and concrete.

Disciplines
Structures and Materials

Comments
This paper is from *Proc. SPIE* 9439, Smart Materials and Nondestructive Evaluation for Energy Systems 2015, 943902 (March 27, 2015); doi:10.1117/12.2086279. Posted with permission.

Needs and opportunities: nondestructive evaluation for energy systems

Leonard J. Bond
Center for Nondestructive Evaluation, Iowa State University
1915 Scholl Road, Ames, IA, USA 50011-3041

ABSTRACT

Advanced manufacturing and new energy systems are presenting a wide variety of challenges for nondestructive testing and evaluation (NDT/NDE). This paper discusses the state of the art, needs and opportunities for NDE to provide reliable, effective and economic inspection and monitoring for energy systems. It introduces issues of materials, defects and allowables, the evolution of advanced NDT and NDE and then considers examples of NDE for energy systems. These include applications in the petrochemical industry, advanced and additive manufacturing, solar cells, wind turbines, nuclear systems and some underlying issues of large scale composites, pipes and concrete.

Keywords: nondestructive testing, review, energy systems

1. INTRODUCTION

The energy technology landscape is in a state of flux. There are those such as Rifkin[1], who wrote about the 3rd Industrial Revolution, with five pillars in solar, wind, hydro, geothermal, waves, and biomass, who see a revolutionary transformation in the technologies employed to meet energy needs. Others are more conservative and see only a much slower evolution and an energy landscape which will maintain or transition with much of what is currently used, including natural gas and clean-coal, and to which can potentially be added new nuclear power for carbon free base-load electricity generation using small modular reactors (SMR"s). The situation is further complicated in the US by advanced oil/gas extraction technologies, commonly known as fracking, and global oil price drops, including the effects of the lower price relative to the production cost for some higher cost extraction technologies. In the energy landscape in the shorter and medium term there are a number of common threads which appear to emerge[2] and these do include some increased use of gas as a cleaner source of energy and power, but there are growing concerns about price instability and security of supplies, particularly in Europe. There is expected to be rapid development of at least some renewable energy sources, but market penetration remains unclear and in some scenarios there is renewed interest in nuclear power due to the long-term resource availability and the CO2-free nature of this power generation. There is expected to be increased investment in the development of clean coal technologies, including carbon dioxide capture and storage, designed to use the huge global resources of coal more cleanly. As new renewable technologies are deployed they will require new distributed power plants, new energy storage technologies, including potentially using hydrogen, leverage of the internet and symbiotic technologies, all potentially combined with a transition of transportation to electric and fuel cells. Such an industrial revolution would return (some) high technology manufacturing to the USA, include new (high) technology, new materials, new manufacturing process, new material fabrication, challenges from new stressor effects on systems, different degradation and aging phenomena, new needs for materials state awareness and life prediction, all of which bring opportunities and challenges in a globalized industry for NDT and research in advanced monitoring/diagnostics, and prognostics.

Under the new energy economy the Nation (USA) is faced with an enormous task if it is to make the least painful transition from its current energy sources (chiefly coal, petroleum and natural gas) to ones more abundant, and ultimately to those that are inexhaustible. This transition will require an unprecedentedly large and rapid shift to different, if not new, technologies. In this transition, the role of nondestructive evaluation (NDE) is certainly clear to its practitioners, but unappreciated or ignored by almost everyone else. It will not be possible to rely on accumulated wisdom to predict the safety, reliability and predicted lifetime of the new components that must be developed. Yet such knowledge can have a major effect on the cost of the new energy systems as they are deployed industrially[3]. This vision and need is not new: the statement was first made in 1978 by James Kane, then Associate Director, Basic Energy Sciences, U.S. Department of Energy. It remains equally, if not more true today as the global community seeks to provide sustainable energy and looks to move to low or no carbon energy sources.

*bondlj@iastate.edu; phone 1-515-294-8152; fax 1-555-294-7771; http://www.cnde.iastate.edu

Smart Materials and Nondestructive Evaluation for Energy Systems 2015, edited by Norbert G. Meyendorf,
Proc. of SPIE Vol. 9439, 943902 · © 2015 SPIE · CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2086279

As the energy economy goes through a transition one must ask what are the needs and opportunities for NDT/NDE, structural health monitoring and prognostics? A major challenge is found in the economics of operations and maintenance, including NDT, particularly when applied to renewable energy technologies. For example the wind energy operations and maintenance (O&M) costs are found to easily have an average share over the lifetime of the turbine of approximately 20%-25% of total levelized cost per kWh[4]. The deployment of monitoring/inspection is logistically clearly very different and can be more expensive, and more challenging, than when compared with those used for a large baseload generating facility. Increasingly NDT becomes part of a wider plant condition based maintenance (CBM) or structural health management (SHM) program. In looking at the technologies encountered in energy systems there are clearly some common elements which can be inspected using established NDT technologies, or variants of them: e.g. for pressure vessels, pipes and concrete[5,6]. For some energy technologies, such as solar, there are specific materials, fabrication scales and geometries that are more closely related to challenges faced in the semi-conductor industry than for most current energy or at least electricity systems[7].

There is a significant history which considers the development and application of NDT/NDE and prognostics to a wide range of the more energy technologies [e.g.,[8,9]]. There is also extensive literature that considers and documents typical damage mechanisms. This paper considers aspects of materials, defects and allowables (section 2), the evolution of NDT/NDE (section 3) and then discusses some examples of advanced NDE for energy systems (section 4).

2. MATERIALS, DEFECTS AND ALLOWABLES

For effective inspections it is necessary to understand the basic properties of materials, particularly in terms of the "fundamental interactions of the energy (i.e. ultrasound, electromagnetic field, thermal etc.)" used to nondestructively examine a medium. It is then necessary to understand the type, shape, size and significance of defects, including what features/anomalies are considered to be allowable at the time of fabrication, and where an allowable anomaly is a local non-uniformity that is insignificant in terms of its impact on performance. In materials assessments the determination of fitness for service or adequacy of quality requires understanding of the influence of damage on structural allowables (Figure 1) and quantification of "manufacturing acceptable features" with criteria for acceptable "anomalies." Such assessments are becoming increasingly both important and challenging with new materials, e.g. composites, and new manufacturing, e.g. additive manufacturing. In an item it is typically not just bulk or surface damage and degradation, but assessments can include quality of joints, micro-cracks and pores and well as a diverse range of in-service phenomena, including impacts. In assessing any NDT technologies capabilities it is then the measurement of its performance, such as with a probability of detection (POD) for a discrete defect, and an assessment of material state or signature, such as grain size/shape in bulk materials, which is needed. However, the nondestructive determination of such signatures and mechanical properties are considered to be a holy grail in NDE[10]. Desired properties can include complex effects, such as combinations of texture, applied stress and temperature.

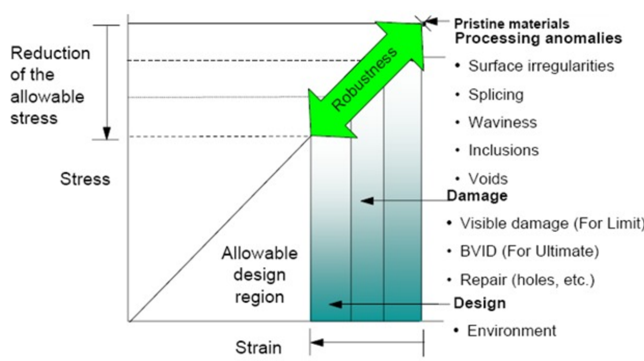

Figure 1. Concept of allowables for a composit material and imperfections effect in reducing design space.

There is a merging of what was considered to be materials characterization and more tradition NDE, particularly in the context of material state awareness and prognostics, in ideas that were formulated by Thompson[11]. Traditional nondestructive evaluation (NDE) was most commonly applied to metals and it was a matter of detection of an anomaly, followed by determination of a size and location. Nondestructive materials characterization is seeking to characterize much more including microstructure (stress, strain, grain-size, moduli, fatigue, fracture toughness) and to evaluate/determine local maps of material properties prior to and after the formation of discernable flaw. The move to provide a more complete materials characterization is important to assessing infrastructure reliability and safety. This is because in some cases the first crack can be catastrophic, due to characteristics such as a zero tearing modulus. Identification of parts of a structure with anomalous or high load is required to guide more focused nondestructive testing, and SHM technologies, to regions with a high propensity to fail. Monitoring such areas can give data to provide an early warning of potential for loss of structural integrity prior to flaw formation and enable earlier and accurate lifetime prediction.

The detailed understanding of microstructure must be a key ingredient in development of state awareness strategies. The connection between NDE measurements and structural performance is then a goal and this is shown in schematic form as Figure 2. In progressing through the process to predict structural performance based on NDE data, each link has it challenges. There are issues on non-uniqueness in the inversion or linking a measured parameter to performance relationships. There can be inadequate sensitivity of NDE tools to key parameters, particularly with regard to measurement scales and early damage, which are all compounded by limitations of the theoretical base for such linkages. There are moves to use of novel NDE technologies (e.g. backscatter ultrasound) for microstructural characterization tools as well as for flaw detection. Adequate sensitivity to early damage or change is critical with the need to be able to assess the progression of damage *before* cracks form. Tools are needed for quantification of the initial state and to check for evolution of damage when possible, and to provide validation of prognostic calls. These limitations and challenges tend to force the use of a stochastic approach.

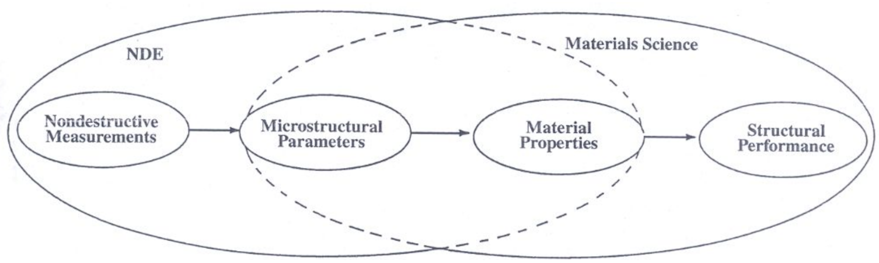

Figure 2. Schematic showing progression from NDE measurements to structural performance.

For in-service NDE it is critical to understand the stressors and how these relate to degradation mechanisms. In general terms aging degradation mechanisms are classified into: (a) **Internal**, that is changes to microstructure or chemical composition, a change in intrinsic properties (thermal aging, creep, irradiation damage, etc.), and (b) **Imposed**, physical damage on the component, which can be in the form of metal loss (corrosion, wear) or cracking or deformation (stress-corrosion, deformation, cracking).

In many cases a flaw is only detectable by traditional NDE relatively late in a components life. If there are high loads and risk of rapid growth of defects to failure, infrequent inspections can cause significant defects to be undetected. With distributed energy technologies, such as a wind turbine farm, where there can be many dozens, if not hundreds of turbines spread out of a large geographic area, limited numbers of inspections, particularly with items of relatively low capital value, is causing attention to move to embedded structural health monitoring. The phenomenon of aging degradation in materials are complex. They require sophisticated, state of the art science and technology procedures to effectively manage it and ensure safe and reliable operation. In this process it is not only technology which is involved, but an effective management system is needed in order to correctly implement mitigation or monitoring actions.

For aging management the necessary codes, standards and best practices are reasonably well established in high technology industries, such a nuclear power, where in the USA the Nuclear Regulatory Commission provides oversight and guidance. Nuclear power plants are considering prognostics and health management for both active and passive components, including on-line monitoring[12]. In some energy technologies such as for oil/gas the American Petroleum Institute (API) provides standards and recommended practice. For example a comprehensive review of "Damage mechanisms Affecting Fixed equipment in the Refining Industry," including suggested inspection approaches is given in API RP 571[13]. Both inspection and repair for in-service piping systems are also addressed[14,15].

In looking at renewable energy systems there are NDT challenges in providing technically adequate and economic testing methods for turbine blades, turbine towers and condition monitoring of gearboxes, rotor hubs and electrical equipment. Offshore wind, in the USA, wave and tidal power are all at an earlier stage of development. Providing inspection and monitoring for achievement of satisfactory availability will undoubtedly be a major challenge since repairs in the hostile marine environment will be exceptionally difficult.

3. EVOLUTION OF ADVANCED NONDESTRUCTIVE TESTING AND EVALUATION

Nondestructive testing/evaluation (NDT/NDE) in its industrial implementation, is a mature technology, guided in large part by codes and standards. The test equipment market was estimated to be over $1.39B in 2011 and to reach $2.03B by 2016[16]. The costs and added value of inspection/quality services is clearly many times that for the equipment market, but reliable estimates are not generally agreed upon. It is however clear that the applications of NDT/NDE are growing to include; aging infrastructure, new materials and new manufacturing processes, together with the growing global equipment market. The range of technologies being deployed in NDT/NDE and SHM is also evolving.

The science and technology that is now employed in NDE, advanced quality assurance and component life management has been developed over a period of more than 40 years[8]. In the 1970s as more advanced technology systems were designed for use in "high-risk" technologies such as nuclear power and advanced aerospace, it was recognized that there was a need to better understand the effects of increasingly severe and hostile environments on materials and the significance of defects, in terms of potential for failure. A science base for the theory and measurement of equipment aging, including the use of accelerated aging programs, was established. In addition, it was seen that the capabilities of then available nondestructive testing (NDT) were limited, and there was a lack of an adequate science base for NDT to become a quantitative science. It was necessary to improve the reliability of inspection and relate size and types of defects to the effect that they have on performance or potential for loss of structural integrity. Several major programs were initiated to provide the required science base, including one sponsored by the United States Air Force-Defense Advanced Research Project Agency (USAF-DARPA), which considered the development of quantitative nondestructive evaluation (QNDE) to meet the needs of the aerospace community. The integration of materials, defects and inspection was achieved through the advent of fracture mechanics, which was greatly enhanced through the ever-improving capabilities of finite element analysis, which was in turn largely facilitated by the availability of ever-more-powerful computer systems. The philosophies of damage tolerance and retirement-for-cause were developed and applied in the 1970s and early 1980s for application to critical aircraft engine components, at all phases of the life-cycle design, manufacture and maintenance. At the same time, other groups of engineers and scientists were considering equally challenging problems of ensuring structural integrity in the nuclear power industry and in the oil and gas industries, in particular, for structures in the North Sea. During the 1970s and '80s great progress was made in both materials science and QNDE in terms of providing a greatly enhanced science base for NDE, new sensors, instrumentation and data analysis tools for application at both the time of manufacture and during periodic inspection of some types of items in service.

The initial focus of much of the research within this emerging community was on metals. This is now expanding into advanced composites and ceramics, and being driven further with new fabrication approaches such as with additive manufacturing. The range of fields of application has also now expanded into civil engineering. Novel integrating design approaches such as unified life-cycle engineering (ULCE) were proposed and partially applied in various forms of concurrent engineering. The full power and potential of this approach was limited by then available materials science and in particular, the computation power needed to perform many of the design optimizations at a reasonable cost and within a reasonable time. UCLE was envisioned as a family of computer-based tools for complete life-cycle analysis that would enable optimizations and trade-offs to be performed at the time of initial design development. In the 1980s and early 1990s, it was increasingly recognized that structural assessment, including quantification and evaluation of defect and defect populations was not all that was required to evaluate the remaining safe-life for complex systems. It was necessary to identify and characterize discrete defects, cracks and corrosion, and determine a rate of growth, investigate the probability of occurrence and probability of detection (POD). It was also becoming clear that there was a need to provide measurements of materials state and changes in bulk material properties caused by the aging of the materials and the accumulation of "damage," due to stressors.

The development of the science for damage mechanics and tools to quantify the properties of critical structures became a priority. Studies considered methods for the combination of damage and fracture mechanics, where the effects of damage are seen in micro-cracks and other physical-chemical changes, "short-crack" growth phenomena occur and macro-cracks described with linear elastic fracture mechanics interact under the influence of a multitude of both physical and chemical environmental factors. The complexity of the phenomena is further increased by inclusion of consideration of "random acts," impacts, explosions and other short duration transient events, as well as longer term daily and seasonal thermal and chemical loading operational cycles.

What was initially called predictive engineering[8] and was subsequently called "prognostics" was first applied to active components in CBM and is now being considered for passive structures subject to aging and potential life extension[12]. It is becoming a family of models, science and measurement technology tools, for use in the integrated methodology, which seeks to provide the framework needed to assess a system, predict a remaining safe-life, formulate and test strategies for mitigation and minimization of the rate of degradation.

4. EXAMPLES OF ADVANCED NDE FOR ENERGY SYSTEMS

In parallel with the development of new energy systems, particularly with regard to renewable energy there has been the development of advanced NDE techniques/tools which move beyond those currently employed and referenced in codes and standards. NDE was traditionally viewed as a quality assurance tool, a check on workmanship, an added cost, necessary to ensure fitness for service, with development being a drive to push for detection of small flaws (as stresses increase) and to give data to enable life extension (retirement for cause). Newer model-based approaches to NDE are providing simulations for inspection optimization, data interpretation, training, and are linked to materials characterization studies where understanding of physics enables interpretation of results. As technologies and applications emerge there are opportunities with guidance in the design of parts and inspection methods and interpretation of POD, including formal modal assisted probability of detection (MAPOD) and wider ranging performance reliability studies.

Some examples of the state of NDE in different energy industries are considered.

4.1 Petrochemical Industry

NDE is extensively employed in extraction, refining and distribution systems, including the vast lengths of natural gas and oil pipelines. The petro-chemical community is now working towards a new document that will consider many of what that community considers to be the advanced NDE techniques[17], as listed in Table 1. For this part of the energy community more advanced NDE techniques are somewhat "black box" technologies, those which are not easily or readily understood by plant engineers.

A particular challenge being addressed is to ensure the integrity of the extensive network of gas and oil pipelines in operation in the USA, and globally. Many of these pipelines have been in operation for many years and it is essential to ensure their continuing safety. For these pipelines, it is important that the materials have the structural integrity to withstand the necessary pressurization without failure. In-line inspection (ILI) "smart pigs" using magnetic flux leakage (MFL) are commonly used to nondestructively detect damage such as cracks or metal loss in the pipeline materials. This ILI information alone, however, is often not enough to determine the pressure rating for the safe operation of the pipeline. In order to determine the most accurate pressure rating of a pipeline and what other threats might become apparent over time, it is crucial to know what the material properties of the pipe are. In many cases, the only adequate method to provide material properties is to remove and destructively test samples. To better predict performance, the local mechanical properties of the pipeline – yield strength, tensile strength, fracture toughness, and transition temperature, for example – should be determined. In some cases, these properties have been shown to correlate with ultrasonic and electromagnetic properties which can be measured nondestructively. This paper will provide a review of the current state of the art for both destructive and nondestructive techniques currently used for pipelines, together with a description of the various nondestructive measurements that potentially could be used to estimate the mechanical properties of interest[18].

Table 1. Summary of some advanced NDE technologies being considered in the petrochemical industry.

Acoustic Emission (AE)	A technique for detecting transient elastic waves in a material undergoing localized cracking or corrosion.
Automated Ultrasonic Backscatter Technique (AUB)	A collection of ultrasonic techniques for detecting a high-temperature hydrogen attack *(*HTHA*)* in equipment that is documented in API RP 941.
Computer Aided Radiography (CAR)	Computer based image processing tools for enhancement and manipulation of RTR images to improve resolution and focus on areas of interest in a digital radiograph.
Eddy Current Array (ECA)	A technique that drives multiple eddy current coils placed together in the same probe assembly for flaw detection and sizing of surface cracks.
Infrared Thermography (IR)	A nonintrusive, noncontact system for mapping thermal patterns on the surface of an object using infrared detectors.
In-Line Inspection (ILI)	The inspection of pipe and pipelines using “smart pigs” (both tethered and non-tethered) that use primarily UT/MFL for detection and sizing of damage.
Internal Rotating Inspection System (IRIS)	An ultrasonic technique for detecting and sizing corrosion in pipe and tubing using an internally inserted probe that generates sound waves.
Laser Scanning of Coke Drums	A profilemetry technique for creating a profile of in-service coke drum deformation sometimes combined with other advanced NDE techniques such as video and ultrasonics.
Long Range Ultrasonic Testing (LRUT)	A technique that uses low frequency guided wave ultrasonics (GWU) for detection of internal and/or external corrosion (CUI) in pipe and tubing.
Magnetic Flux Leakage (MFL)	A technique that is used to detect corrosion in steel piping and storage tanks whereby a magnetic detector that is placed between the poles of the magnet detect a leakage field where corrosion is present.
Meandering Winding Magnetometer Array (MWMA)	A relatively new technique for detecting and characterizing corrosion and cracking using multiple inductive sensors.
Phased Array Ultrasonic Technique (PAU)	A set of UT probes made up of multiple small elements each of which is pulsed individually with computer-calculated timing which can be used to inspect more complex geometries that are difficult and much slower to inspect with single probes.
Pulsed Eddy Current (PEC)	A technique for measuring wall thicknesses on insulated equipment without having to remove the insulation and jacketing.
Real Time Radiography (RTR)	A radiographic technique that produces an almost immediate electronic digital image of the item being inspected/ radiated rather than on film.
Remote Field Eddy Current (RFEC)	An electromagnetic technique for finding defects in piping and tubing using an internally inserted probe that generates a magnetic field.
Remote Visual Inspection (RVI)	Refers to methods of enhanced visual examination means of visual aids including video borescopes, push cameras, pan/tilt/zoom cameras and robotic crawlers.

4.2 Advanced and Additive Manufacturing

Advanced materials and manufacturing processes, many of which are associated with new energy systems are moving beyond traditional metals to include a diversity of materials ranging from powder metals, to ceramics and composites. Among the challenges in manufacturing is providing sensors that can operate at high temperatures and be integrated into a process, clearly moving beyond traditional NDE implementations.

For a diverse range of advanced manufacturing there is proving to be a need to move QA/QC metrology beyond dimensional characterization. Material characterization is looking to provide descriptors for discrete features, such as pores and cracks, texture, together with hardness and moduli. The trend is to seek flexibility, and transparency for metrology tools for manufacturing metrology that can be integrated into manufacturing systems, have short measurement times, and provide automated data processing. In such systems there is a need to be accurate and to provide reduced measuring errors and uncertainty, and be applied using an increasing variety of measuring techniques, many based on traditional NDE physics[19].

A new area is that of additive manufacturing which is becoming almost universally considered as an option in new and advanced manufacturing. The cost price of 3D printers is falling, and the software used to program them is becoming simpler to use. High-performance fabricators are now engaging this technology for both rapid prototyping and small bath fabrication. In 2013, 3D printer sales, materials and associated services reached \$2.5bn (€1.8bn, £1.5bn) worldwide, according to research firm Canalys[20]. This figure was expected to rise to \$3.8bn (€2.8bn, £2.2bn) in 2014, before reaching \$16.2bn (€11.9bn, £9.6bn) by 2018. That said there is a real challenge in ensuring fitness for service and inspection of just the finished part is not adequate, it is necessary to provide new inspections. A comparison of NDE technologies being applied to powder metal parts is shown in Table 2[21-23].

Table 2. Comparison of application of various NDE[23] after[21,22].

		Applicability to PM Parts (a)			
Method	**Measured/detected**	**Green**	**Sintered**	**Advantages**	**Disadvantages**
X-ray radiography	Density variations, cracks, inclusions	A	A	Can be automated	Relatively high initial cost, radiation hazard
Computed tomography	Density variations, cracks, inclusions	A	A	Can be automated; pinpoint defect location	High initial cost; highly trained operator required; radiation hazard
Gamma-ray density determination	Density variations	A	A	High resolution and accuracy; relatively fast	High initial cost; radiation hazard
Ultrasonic imaging: C-scan	Density variations, cracks	C	A	Sensitive to cracks: fast	Coupling agent required
High frequency ultrasonic imaging: e.g. AM or SLAM	Density variations, cracks	C	C	Fast; high resolution	High initial cost; coupling agent required
Resonance testing	Overall density, cracks	D	B	Low cost; fast	Does not give information on defect location
Acoustic emission	Cracking during pressing and ejection	C	C	Low cost	Exploratory
Thermal wave imaging	Subsurface cracks, density variations	D	C	No coupling agent required	Flat or convex surfaces only; sensitive to edge effects
Electrical resistivity	Subsurface cracks, density variations, degree of sinter	A	A	Low cost; portable, high potential for use on green compacts	Sensitive to edge effects
Eddy current/magnetic bridge	Cracks, overall density, hardness, chemistry	A	A	Low cost, fast, can be automated; used on PM valve seat inserts	Now deployed
Magnetic particle inspection	Surface and near-surface cracks	C	A	Simple to operate; low cost	Slow; operator sensitive
Liquid dye penetrant inspection	Surface cracks	C	D	Low cost	Very slow; cracks must intersect surface
Pore pressure rupture/gas permability	Laminations, ejections, cracks, sintered density variations	A	A	Low cost, simple, fast	Gas-tight fixture required; cracks in green parts must intersect surface

(a) A, has been used in the production of commercial PM parts; B, under development for use in PM; C, could be developed for use in PM, but no published trials yet; D, low probability of successful application to PM.

4.3 Solar Cells

Solar power generation technologies come in a diversity of types, shapes and sizes, which range from those using large mirrors as concentrators to heat a furnace, to the solar cell for a domestic path light. The larger scale systems can employ concrete, as well as a diverse range of piping, heat exchangers and associated instrumentation and controls. With the exception of inspection of mirrors the NDT for such systems is that typically employed for a wide range of power plants and civil infrastructure, which can include many of the techniques listed in Table 1.

For many forms of semi-conductor technology based solar panels and solar cells the fabrication involves multi-layer materials. Common test techniques for silicon panels are photoluminescence, electroluminescence, laser beam induced current[24], dark lock-in thermograph[25], and machine vision. Such techniques mostly provide information on external defects[26]. To look inside fabrications, scanning acoustic microscopy (SAM) has been used by several groups, in much the same way as it is employed to inspect microprocessors and similar semi-conductor devices. The use of SAM for inspection of wafer junctions has been discussed by Dimroth et al.[27]. SAM in the frequency range 15 – 175 MHz. has been used by Curratis et al.[28] as a tool for failure analysis.

In addition to acoustic/ultrasonic methods a range of other probing modalities are being reported. For example a range of thermography methods have been employed [e.g.,[29]]. Electromagnetic methods have included terahertz imaging using both time-domain and spectroscopy, as used by Jepsen et al.[30] on power electronic devices and other application, including solar cells. Other evolutions and combined mode probes have also been reported. Laser terahertz emission microscopy has been discussed by Nakanishi et al.[31] and Salek et al.[32] which combines an optical laser and a THz. image. What can be considered to be more exotic methods include laser - superconducting quantum interference devices (laser-SQUID)[33] and electro luminescence methods[34]. The DC current in solar panels has also been mapped using high critical temperature superconductor superconducting interference devices (HTS-SQUID)[35].

4.4 Wind Turbines

There has been a significant interest in NDT and condition monitoring for application to wind turbines for more than 25 years[36]. Wind turbine blades are a particular challenge given their size and the materials and manufacturing approaches employed, which are closer to those used in composite boat building than to those used for aero-apace composites, such as in the Boeing 787. A review of degradation and damage encountered in these units and NDT for the various parts of these systems have been considered by several authors[37-39]. NDT tools are used throughout the life cycle. For example, for blades at the time of manufacture visual, ultrasound, tap tests, and infrared inspections are all used. In connection with destructive fatigue testing, acoustic emission has been utilized since at least 1993[40]. In-service NDT is focused on blades, bearing, and gears, but also needs to consider the towers and concrete foundations. Given the costs associated with inspection for the increasing number of turbines in use, and there, geographic dispersion, there is currently a move to look at the feasibility of using optical fibers and piezoelectric sensors for on-line monitoring. However there are significant challenges faced in terms of providing a cost effective instrumentation for on-line monitoring and establishing condition based, rather than time based, maintenance.

4.5 Advanced NDE for Nuclear

There are currently three focus areas that are having a significant impact on NDT/NDE in the nuclear power community. These are (i) legacy nuclear power plants, which require aging management and license extension[41], (ii) new build, (there are globally 65 plants under construction January 2015) and (iii) advanced systems, which in the USA includes light water small modular reactors (medium term deployment) and advanced reactors using other coolants which include liquid sodium, molten salts and lead bismuth eutectics[42].

4.5.1 Legacy Plants

In the USA there are currently 100 plants in operation and many of them have either passed the initial 40 year license period or are fast approaching that point. Such plants typically undergo a major refurbishment before they are granted a license extension to enable them to operate for an additional 20 years. The age of plants and interest in license extension has resulted in a significant Department of Energy (DOE) and Electric Power Research Institute (EPRI) program plan[43].

Similar programs are being developed in other countries with legacy plants. In the USA activities are looking to understand the capabilities and limitation of NDE technologies[44] and specifically from the NDE perspective there is significant interest in NDE for the detection and characterization of degradation precursors[45]. In looking at some cracking phenomena the various stages in degradation development present different challenges. As shown in Table 3 for fatigue materials science tools can be deployed to probe for crack nucleation. For short and longer cracks there are significant challenges, particularly in field applications.

Table 3. Measurement approaches for fatigue crack growth, in different stages of development (after Thompson).

Stage of Fatigue	Potential Measurement	Status of Scientific Foundation	Implementation Issues
Crack nucleation	Grain size determination by UT backscatter after manufacturing	Well established for single phase materials Effects of precipitates and grain boundary decorations under study	No major "show stoppers"
Short crack growth	Ultrasonic harmonic generation	Mechanisms for engineering materials under study (dislocations vs. microcracks as sources)	Very challenging measurement in the field
Long crack growth	Deploying tradition NDE in-situ	Broad foundations in place Effects of morphology e.g., closure, subject of ongoing study	Challenging measurement in many field applications.

4.5.2 New Build

There are four reactors currently under construction in the USA. These plants are using current codes and standards and conventional NDT throughout the fabrication process, and these activities are basically outside the scope of the current paper.

4.5.3 Advanced Small Modular Reactors

For the medium term deployments, in the USA, attention is focused on SMR's using light water reactor technology. It is generally being stated that these needs can be met using commercially available capabilities, without the need for further research. The research community is therefore being encouraged to look at advanced reactors, using other coolants including liquid sodium, molten salts and lead bismuth eutectics. In all three cases there are significant challenges, not the least of which is the need to provide NDE and imaging capabilities in high temperature in the range 250-550 C, and in some cases higher, in media such as liquid sodium that are chemically reactive and have conductivity significantly higher than that for water[46,47].

4.6 Large Scale Composites, Pipes and Concrete

In looking at the full spectrum of renewable technologies the interest in tidal and geothermal is growing and attention is starting to address the NDT needs. For geothermal systems, much is comprised of carbon and low alloy steel. Specific needs for improved instrumentation and NDT were identified by Allan[48] and more recently reviewed by Berndt[49]. The NDT technologies are conventional, although the corrosion and specific applications are custom to geothermal, there is much in common with the needs and technologies employed in the petrochemical community [e.g.[13]]. For at least some tidal power applications large composite hydrofoils are being considered. In many ways these "blades" are not totally dissimilar to those used in wind turbines, and a number of the inspection methodologies used in construction and for monitoring can be employed. Some recent work is considering the use of guided waves to monitor critical regions[50].

Concrete is almost ubiquitous to civil engineering structures. For power systems it is a key element in dams, in nuclear, wind turbine base structures, and now also towers and in almost every other form of power plant. NDT for concrete using ultrasonic pulse velocity (UPV) dates back to the availability of relatively inexpensive instruments developed in the 1970's. A variety of other technologies have followed and these have been extensively discussed in the literature[51,52]. Most recently an assessment of the state of the art for concrete structures has been provided by the German, BAM[6]. This review targeted technologies for potential application in nuclear power plant structures, but it is much wider ranging. It includes tools for measurement of the covering and location of steel reinforcement, tendons and ducts, together with assessment of grout condition, and then methods for detecting cracking, voids, delamination and honeycombing in concrete structures. A final section addresses detection of inclusions as well as specific issues relating to assessment of materials condition next to containment liner, including corrosion. Table 4 presents a summary of testing methods for defect detection and degradation assessment in concrete structures.

Table 4. **S**ummary of testing methods for defect detection in concrete structures.

Method	Purpose/Application	Advantages	Limitations
Low frequency ultrasonic (US)-echo with single shear wave transducer-receiver unit	Near surface delaminations	Recordability of near surface delaminations	In case of multiple layers the current techniques cannot distinguish the layers
Low frequency US-echo array with shear wave transducers	Thickness estimation, deep delaminations parallel to the surface	Location of thickness and deep delaminations	Concrete surface must be accessible, influence of dense reinforcement
High frequency US-echo	Steel liner thickness estimation	Method allows for estimation of the remaining cross section after corrosion	Only applicable, if the liner is accessible from the steel surface
US-Phased array with shear wave transducer	Localization of irregular or diagonal cracks	3D-datasets allow for color coded imaging (Contour plots)	Not applicable to net cracking (ASR, AAR, late ettringite formation)
Lamb Waves	Localization of vertical surface cracks	Analysis of the travel time	Not established, further research for concrete required
Rayleigh waves	Localization of surface cracks	Applicable for first crack detection	Limited applicability to multiple cracks
Impact-echo	Thickness estimation, deep delaminations parallel to the surface	Feasibility proved for road infrastructure	Not for near-surface delamination/debonding
Radar (ground penetration radar – GPR)	Detection of cavities, water filled cracks	Digital documentation, depth information	Influence of humidity and salts on dielectric parameters
Acoustic emission	Ultrasound received during active crack growth	Well detectable and localizable areas of cracking	Minimum of 4 US receivers, complicated analysis due to multiple crack growth
Active thermography	Defect detection in the interior of a structure (metal or void inclusions, near surface delaminations)	Documentation of digital images for cracks and other voids parallel to the surface	Time consuming preheating and recording of the cooling down process

Fibre optic sensors Polymer optic fibers (POF)	Identification of surface crack formation, if below externally fixed Bragg grating FOS	Early detection of fracture, monitoring possible FOS and POF have potential for monitoring cracking	POF is under research for its potential to monitor additional parameter (pH, humidity)
Laser shearography	Visualization of surface cracks and deformation	Digital documentation	Investigation of the accessible side only
Pattern recognition	Visualization of surface cracks and deformation	Digital documentation	Investigation of the accessible side only
Photogrammerty	Visualization of surface cracks	Digital documentation	Investigation of the accessible side only

5. CONCLUSIONS

NDT/NDE for energy system applications can be expected to grow in its application: drivers include quality, safety, sustainability and cost of ownership. There will be better and more effective deployment of "Traditional and Advanced NDT" as more diverse energy systems are developed and deployed, new applications of current technologies will be developed. In addition new and emerging capabilities, such as those for solar cells and panels, will be needed. Some general challenges will include handling large data, providing permanent records for inspections, developing and utilizing better equipment, all in the context of increasingly employing automation and robotics. There can be expected to be some integration into manufacturing process monitoring measurement and control, and measurements of material state and mechanical properties, where full characterization of materials will merge activities into those traditional considered to be materials science. There is a trend to increasingly include an NDE or design for testability activity that includes increasing use of models in product development.

In looking across NDE the research and development problems are getting harder, due to design, manufacturing and materials combinations. NDT/NDE is increasingly seen as part of CBM/Prognostics and the total quality manufacturing process. To provide the information desired there is a general need for NDE to be more quantitative and more sensitive, such as for early degradation detection. These trends are requiring new sensors, and integration into manufacturing metrology. There is also a trend to move from NDT/NDE and structural health monitoring (SHM) to true prognostics, that provides remaining/safe life estimation at the system level. These NDT will be used to minimize ownership costs, but challenges will remain in terms of providing economic and effective NDE for decentralized energy generation (e.g. wind turbines) and systems that will be deployed in harsh environments (e.g. off-shore wind, tidal and wave systems). Fully Integration of NDE into engineering and product life cycle – design for inspectability and monitoring. Quantification of uncertainty – (ill-posed problems). Physics has not changed!! Heat, light and sound! (thermography, electromagnetics, ultrasound)

6. ACKNOWLEDGMENTS

This was supported by the Center for Nondestructive Evaluation, an NSF Industry University Cooperative Research Center (IU CRC) at Iowa State University.

REFERENCES

[1] Rifkin, J., "The Third Industrial Revolution: How Lateral Power is Transforming Energy, the Economy, and the World," Palgrave Micmillan, New York (2011).

[2] Farley, J. M., "Energy in the Future – New Challenges for NDT," Proc. 17th World Conf. NDT, 25-28 Oct 2008, Shanghai, China, Paper #541, (2008) http://www.ndt.net/article/wcndt2008/papers/541.pdf

[3] Kane, J. S., "The Importance of Nondestructive Evaluation to Future Energy Systems," Proc. ARPE/AFML Review of Progress in QNDE, AFML-TR-78-205, pp. 145-148 (1997).

[4] Van Dam, J. and Bond, L. J., "Economics of On-line Monitoring of Wind Turbines: Cost Benefit Analysis," Proc. 41st Review of Progress in Quantitative NDE, eds. D. E. Chimenti and, L. J. Bond, (Boise, ID, July, 2014) AIP Conference Proceedings [in press] (2015).

[5] Bond, L. J., Barnard, D. J., Utrata, D., and Jensen, T. C., "Advanced Inspection and Monitoring Technologies for Fresh and Salt Water Pipe Systems", Office of Naval Research, Award # N00014-13-1-0851, p.53, March, 2014.

[6] Wiggenhauser, H., Helmerich, R., Krause, M., Mielentz, F., Niederleithinger, E., Taffe, A., and Wilsch, G., Non-destructive Testing of Nuclear Power Plant Concrete Structures State of the Art Report, BAM Division 8.2 , Berlin, Germany, April 30, 2013.

[7] Kerbs, F. C., "Fabrication and Processing of Polymer Solar Cells: A Review of Printing and Coating Techniques," Solar Energy Materials & Solar Cells, 93, 394–412 (2009).

[8] Bond, L. J., "Predictive Engineering for Aging Infrastructure" (Plenary Paper). In Nondestructive Evaluation of Utilities and Pipelines III, ed. W. G. Reuter, Proceedings SPIE, March 4, 1999, Newport Beach, CA, Vol. 3588, pp. 2-13 (1999).

[9] Bond, L. J., "Moving Beyond Nondestructive Examination to Proactive Management of Materials Degradation," J. Pressure Vessel Technology (ASME), 134 (1) Paper# 014501 (8 pages) (2012) doi: 10.1115/1.4005056.

[10] Thompson, R. B, "Ultrasonic Measurement of Mechanical Properties," IEEE Ultrasonics Symposium, 735-744 (1996).

[11] Thompson, R. B., "Exploring the Implications of Bayesian Approach to Material State Awareness," Workshop on Prognosis of aircraft and space devices, components and systems, AF OSR, Feb. 19-20, 2008 (http://www.ase.uc.edu/~pnagy/NDE/AFOSR%20Prognosis%20Workshop/Abstracts.html - ppt. downloadable).

[12] Coble, J., Ramuhalli, P., Bond, L. J., Hines, W., and Upadhyaya, B, "A Review of Prognostics and Health Management Applications in Nuclear Power Plants," Int. J. Prognostics and Health Management (IJPHM), [in press] (2015).

[13] API RP 571, Damage Mechanisms Affecting Fixed equipment in the Refining Industry.

[14] API Standard 570 – Inspection, Repair, Alteration, and Rerating of In-Service Piping.

[15] API Recommended Practice 574 – Inspection Practices for Piping System Components.

[16] Nikhil Jain, (2012) "Analysis of the Global Nondestructive Test Equipment Market", Frost and Sullivan.

[17] Reynolds, John, (2015), http://info.inspectioneering.com/blog/advanced-nondestructive-examination-nde-development-and-advancements.

[18] Engle, B. J., Smart, L., and Bond, L. J., "Nondestructive Characterization of Pipeline Materials", Proc. 41st Review of Progress in Quantitative NDE, Vol. 34, eds. D. E. Chimenti and, L. J. Bond, (Boise, ID, July, 2014) AIP Conference Proceedings [in press] (2015).

[19] Berthold, J. and Imkamp, D., "Looking at the Future of Manufacturing Metrology: Roadmap Document of the German VDI/VDE Society for Measurement and Automatic Control", J. Sens. Sens. Syst., 2, 1–7 (2013) doi:10.5194/jsss-2-1-201.

[20] Canalys (March 2014), http://www.canalys.com/newsroom/3d-printing-market-grow-us162-billion-2018.

[21] O'Brien, R. C. and James, W. B., "Powder Metallurgy Parts", Nondestructive Evaluation and Quality Control, Vol. 17, ASM Handbook, ASM International, pp. 536-548 (1989).

[22] O'Brian, R. C. and James, W. B., "A Review of Nondestructive Testing Methods and their Applicability to Powder Metallurgy Processing", downloaded December 2013, Hoeganaes Corporation, Riverton, NJ 08077, http://www.gkn.com/hoeganaes/Pages/default.aspx

[23] Bond, L. J., Gray, J. N., Margetan, F. J., Utrata, D., and Anderson, I. E., "NDE for Adding Value to Materials from Metal Powder Processing Advances in Powder Metallurgy & Particulate Materials," Proceedings, PM2014, Compiled by R. A. Chernenkoff and W. B. James, Metal Powder Industries Federation, Part 11, (pp. 11.1-15), pp 1944-1959 (2014).

[24] Israil, M., Kerm, A. G. Y., "Non-destructive Microcracks Detection Techniques in Silicon Solar Cell," Physical Sci. Int. J., 4(8) 1073-1087 (2014).

[25] Straube, H., Wagner, J-M., and Breitenstein, O., "Interpretation of Lock-In Thermography on Thin Film Solar Cells Considering Dissipative and Peltier Contributions," Proc. 10th Int. Conf. on Quantitative IntraRed Thermography, July 27-30, 2010, Quebec, Canada.

[26] Xu, Z., Gao, S., Huang, J., and Wang, Y., "Non-Destructive Testing of Polycrystalline Silicon Solar Panel by Scan Acoustic Microscopy," Advanced Materials Res., 764, pp 9-13 (2013).

[27] Dimroth, F., Grave, M., Beutel, P., Fiedeler, U., Karcher, C., Tibbits, T. N. D., Oliva, E., Siefer, G., Schachtner, M., Wekkeli, A., Bett, A. W., Krause, R., Piccin, M., Blanc, N., Drazek, C., Guiot, E., Ghyselen, B., Salvetat, T.,

Tauzin, A., Signamarcheix, T., Dobrich, A., Hannappel, T., and Schwarzburg, K., "Wafer Bonded Four-junction GaInP/GaAs//GaInAsP/GaInAs Concentrator Solar Cells with 44.7% Efficiency." Prog. Photovolt: Res. Appl., 22, 277–282 (2014).
[28] Czurratis, P., Hoffrogge, P., Brand, S., Altmann, F., and Petzold, M.,"Failure Analysis Using Scanning Acoustic Microscopy for Diagnostics of Electronic Devices and 3D System Integration Technologies, " Proceedings from the 38th International Symposium for Testing and Failure Analysis: November 11-15, 2012, Phoenix Convention Center, Phoenix, Arizona, USA Materials Park, Ohio: ASM International, pp.100-105 (2012).
[29] Breitenstein, O. and Altmann. F., "Inversion of Microscopic Lock-in Thermograms in the Presence of Emissivity Contrast," NDT&E International, 39, 636-640 (2006).
[30] Jepsen, P. U., Jacobsen, R. H., and Keiding, S. R., "Generation and Detection of Terahertz Pulses from Biased Semiconductor Antennas," JOSA B, 13(11), 2424-2436 (1996) dttp://dx.doi.org/10.1364/JOSAB.13.002424
[31] Nakanishi, H., Fujiwara, S., Takayama, K. Kawayama, I., Murakami, H., and Tonouchi, M., "Imaging of a Polycrystalline Silicon Solar Cell Using a Laser Terahertz Emission Microscope," Appl. Phys. Express, 5, 112301 (2012) doi:10.1143/APEX.5.112301
[32] Salek, K. A., Nakanishi, H., Ito, A., Kawayama, I., Murakami, H., and Tonouchi, M., "Laser Terahertz Emission Microscopy Studies of a Polysilicon Solar Cell under the Illumination of Continuous Laser Light", Opt. Eng., 53(3), 031204 (Nov 05, 2013).
[33] Daibo, M., Shikoda, A., and Yoshizawa, M., "Non-contact Evaluation of Semiconductors Using a Laser SQUID Microscope," Physica C: Superconductivity, 372-376, 263–266 (2002).
[34] Pankove, J., Photoluminescence Assessment of Solar Cell Materials," Solar Cells, 2(4) 443–449 (1980).
[35] Miyazaki1, S., Kasuya1, S., Saari1, M. M., Sakai1, K., Kiwa1, T., Tsukamoto, A., Adachi, S., Tanabe, K., and Tsukada1, K., "DC Current Distribution Mapping System of the Solar Panels Using a HTS-SQUID Gradiometer," 11th European Conference on Applied Superconductivity (EUCAS2013) IOP Publishing Journal of Physics: Conference Series 507, 042026 (2014).
[36] Bond, L.J. and Clayton, B.R., "Non-destructive Testing and Condition Monitoring of Wind Turbine Blades," Wind Engineering, 13(1) 19-29 (1989).
[37] Drewry, M. A. and Georgiou, G. A., "A Review of NDT Techniques for Wind Turbines," Insight, 49(3) 137-141 (2007).
[38] Raisutis, R., Jasiuniene, R., Sliteris, R. and Vladisauskas, A., "The Review of Non-Destructive Testing Techniques Suitable for Inspection of the Wind Turbine Blades," Ultragarsas (ultrasouns), 63(1), 26-30 (2008).
[39] Yang, B. and Sun, D., "Testing, Inspecting and Monitoring Techniques for Wind Turbine Blades: A Survey," Renewable and Sustainable Energy Reviews, 22, 515-526 (2013).
[40] Wei, J. and McCarty, J. "Acoustic Emission Evaluation of Composite Wind Turbine Blades During Fatigue Testing," Wind Engineering, 17(6) 266-274 (1993).
[41] Bond, L. J. "Old Reactors, New Tricks," IEEE Spectrum, 49(8), 30-35 (2012).
[42] World Nuclear Organization, http://www.world-nuclear.org/info/country-profiles/countries-T-Z/USA--Nuclear-Power/
[43] DOE-NE Light Water Reactor Sustainability Program and EPRI Long-Term Operations Program – Joint Research and Development plan, Idaho National Laboratory, INL/EXT -12-24562, Revision 3, (April 2014).
[44] Meyer, R. M., Ramuhalli, P., Coble, J. B., and Bond, L. J., Advanced Instrumentation, Information and Control Technologies: Nondestructive examination technologies – FY 11 Report, Pacific Northwest National Laboratory – PNNL – 20671
[45] Ramuhalli, P., Meyer, R. M., Fricke, J. M. Coble, J. B., Griffin, J. W., Pitman, S. G., Dahl, M. E., Kafentzis, T. A. and Roosendaal, T. J., Nondestructive Evaluation (NDE) Detection and Characterization of Degradation Precursors, PNNL Report # 21682.
[46] Bilgunde, P. N. and Bond, L. J., "Analysis of High Temperature Ultrasonic Transducer Performance in Small Modular Reactors," Proc., NPIC & HMIT 2015 Conference, February 23–26, 2015, Charlotte, North Carolina, American Nuclear Society [in press] (2015).
[47] Quaddes, M. R., Bond, L. J., and Bowler, J. R., "Measurement Challenges Due to the Noise Effect for an Eddy Current Probe," Proc. NPIC & HMIT 2015 Conference, February 23–26, 2015, Charlotte, North Carolina, American Nuclear Society [in press] (2015).
[48] Allan, M. L., Survey of Operation and Maintenance Related Materials Needs in Geothermal Power Plants, Brookhaven National Laboratory, Report BNL 65677 (1998).

[49] Berndt, M. L., Non-destructive Testing Methods for Geothermal Piping," Brookhaven National Laboratory, Report BNL – 86166 (2001).
[50] Raišutis, R., Mažeika, L. Samaitis, V., Jankauskas, A., Mayorga, P., Garcia, A., Correa, M., and Neal, B., "Application of Ultrasonic Guided Waves for Investigation of Composite Constructional Components of Tidal Power Plants**,"** The 12th International Conference of the Slovenian Society for Non-Destructive Testing, Application of Contemporary Non-Destructive Testing in Engineering, September 4-6, 2013, Portorož, Slovenia.
[51] Bond, L. J., Kepler, W. K., and Frangopole, D. M., "Improved Assessment of Mass Concrete Dams Using Acoustic Travel Time Tomography. Part I, Theory," Construction and Building Materials, 14, 133-146 (2000).
[52] Malhotra, V. M. and Carion, N. J., CRC handbook on NDT Concrete, CRC Press (Boca Raton) (1991).