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Through the looking glass: The future for NDE?

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Abstract

Nondestructive testing (NDT) is a mature industry, with global equipment sales fast moving towards $2B. per year. The use of conventional NDT will grow in developing countries and in developed countries the challenges will include those associated with maintaining aging infrastructure. For some systems the future will move to structural health monitoring (SHM) and for others into integration of online measurements in manufacturing. Nondestructive Evaluation (NDE) is a multi-disciplinary area of endeavor that has its origins in materials science and NDT. It seeks to provide *an adequate science base for NDT to become a quantitative science*. It was seen to be necessary to better detect, size and type defects, improve the reliability of inspection, and probability of detection (POD). There is particular interest in estimating the potential defects could have on performance or potential for loss of structural integrity, under various loading or stressor conditions, and ultimately implement risk-based reliability assessments. NDE must be seen more as a part of the wide field of engineering, as an interdisciplinary endeavor, that brings together the expertise of materials science and metrology, together with the underlying physics for inspection methods, as well as statistics, computers, robotics and software. The adoption of advanced manufacturing, will require new metrology tools and methods to provide data for assessing new materials including powder metals, as used in additive manufacturing, and various composites. The lessons from the past proceedings of this conference series include that the problems faced today are harder than was expected during the first decade of quantitative NDE research. Even with new types of transducers and much improved A/D and powerful computers new approaches and more basic measurement physics being understood, new insights are needed to provide the data needed to solve many real-world NDE problems, to understand and measure early degradation and to give the required data for remaining safe life or prognostic prediction.

Keywords

Nondestructive Evaluation, Prognostics, Structural Health Monitoring

Disciplines

Engineering Education | Engineering Physics | Structural Materials | Structures and Materials

Comments

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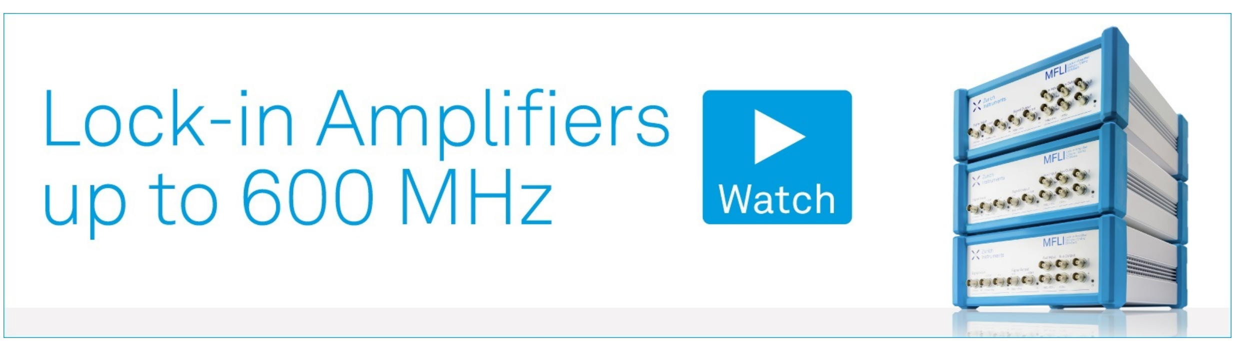

Through the Looking Glass: The Future for NDE?

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Abstract. Nondestructive testing (NDT) is a mature industry, with global equipment sales fast moving towards $2B. per year. The use of conventional NDT will grow in developing countries and in developed countries the challenges will include those associated with maintaining aging infrastructure. For some systems the future will move to structural health monitoring (SHM) and for others into integration of online measurements in manufacturing. Nondestructive Evaluation (NDE) is a multi-disciplinary area of endeavor that has its origins in materials science and NDT. It seeks to provide *an adequate science base for NDT to become a quantitative science*. It was seen to be necessary to better detect, size and type defects, improve the reliability of inspection, and probability of detection (POD). There is particular interest in estimating the potential defects could have on performance or potential for loss of structural integrity, under various loading or stressor conditions, and ultimately implement risk-based reliability assessments. NDE must be seen more as a part of the wide field of engineering, as an interdisciplinary endeavor, that brings together the expertise of materials science and metrology, together with the underlying physics for inspection methods, as well as statistics, computers, robotics and software. The adoption of advanced manufacturing, will require new metrology tools and methods to provide data for assessing new materials including powder metals, as used in additive manufacturing, and various composites. The lessons from the past proceedings of this conference series include that the problems faced today are harder than was expected during the first decade of quantitative NDE research. Even with new types of transducers and much improved A/D and powerful computers new approaches and more basic measurement physics being understood, new insights are needed to provide the data needed to solve many real-world NDE problems, to understand and measure early degradation and to give the required data for remaining safe life or prognostic prediction.

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INTRODUCTION

The science and technology that is now employed in NDE, and an increasing range of related endeavor's, has been developed over a period of much more than the 40 years of existence of this meeting. Its roots go back to the activities that spawned NDT; the measurement components which employ radiography followed from the discovery of X-rays in 1895 by Wilhelm Roentgen, ultrasonics had its roots in physical acoustics and SONAR from about 1912, and many millennia earlier in "tap" testing for pottery condition assessment [1] and in electromagnetic methods for NDT these can be traced back to work in the 1880's.

The needs for applications of NDT received a real boost during World War II, and its use grew further in the post-war period, but it remained a workmanship standard and a tool for use in periodic testing. In the 1960's and into the early 1970s, there was a growing fundamental understanding of the significance of flaws in metal structures and their subsequent impact on performance. This was, in part, driven by the desire for safety with the emergence and utilization of high-cost, high-risk technologies in defense systems and in the civilian aerospace and energy communities, including nuclear power. It was recognized in Europe and the USA, and then other developed countries that there was a need to better understand the effects of increasingly severe and hostile environments on materials. It was also becoming clear that there was a need to better understand the significance of defects, in terms of component life, the potential which they had to cause failure and the statistical performance capabilities of both inspectors and inspection methods. A science base for the theory and measurement of materials characterization, including the use of accelerated aging programs, began to be developed [e.g. 2]. It was increasingly seen that the capabilities of then available nondestructive testing (NDT) were limited, and that there was a *lack of an adequate science base for NDT to become a quantitative science*. It was also seen to be necessary to improve the understanding of the science for interrogating energy-material interactions on which reliability of inspection is based. There followed the desire to better relate types and size of defects to their structural significance, under particular operating conditions, and the potential effect that they have on performance or potential for loss of

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structural integrity, and to quantify NDT performance with probability of detection (POD) and ultimately implement risk-based reliability assessments [3].

Several major research programs were initiated to provide the required science base, including one which considered the development of what was named *quantitative nondestructive evaluation (QNDE),* which sought to meet the needs of the aerospace community. This was sponsored by the United States Air Force and Defense Advanced Research Project Agency (USAF-DARPA). It is this activity which gave rise to the “RPQNDE” or “QNDE” Meeting” series [4, 5]. During the same time period internationally several parallel initiatives started to develop to meet inspection needs in the defense community in various NATO countries and there were also programs focused on civilian infrastructure. Examples of developments included, in Germany, the establishment of the Fraunhofer Institut für Zerstörungsfreie Prüfverfahren [Nondestructive Testing] (IZFP) in Saarbrucken, in the United Kingdom (UK) it was the U.K. Atomic Energy Authority (UKAEA), Harwell NDT Center, which initially looked at nuclear needs and the British Gas programs for pipeline inspection. These activities all largely followed the growth of high technology energy (principally nuclear, and then off shore oil and gas), aero-space and defense systems. These programs engaged a diverse range of both academic and industrial researchers, who had previously had little or no connection with conventional NDT and the practitioner community [4, 5].

The story of the development of NDE and the growth in the application of NDT/NDE is one that has seen the emergence of an interdisciplinary field of endeavor that addresses safety, reliability, quality and now almost all aspects of cost in the component and system life-cycle. For some NDE is viewed as a quality assurance tool to ensure fitness for service, with a drive to push for detection of small flaws (as stresses increase) and enable life extension (retirement-for-cause). As witnessed by this meeting series it is much more than this. It is a story that has leveraged advances in materials science, interactions between various interrogating modalities (optical, ultrasonic, thermal, electromagnetic) and materials, advances in instrumentation and sensors, in computers for both modeling and data processing, together with advances in electronics and robotics. This field of endeavor is now being increasingly driven by the needs to maintain product quality and safety and also constrain total life cycle costs. It has become an integral part of advanced materials manufacturing QA/QC and a modality that can enable management of an increasing inventory of aging assets and infrastructure. Its growth has tended to be driven by failures in systems, such as the early de Havilland DH 106 (Comet) crashes, the Aloha airline crash (1988) and the United, Sioux City crash (1989), together with corresponding events in other industries, but it is more than just a tool to improve safety. It is an enabler for understanding and characterizing materials on the engineering scale, it is a bridge that connects the insights of “slice and dice” for materials examination in the laboratory to inspection at manufacture, during fabrication/integration, installation and during service. It can be an integral part of the design and optimization of the life cycle, which can guide materials selection, contribute to setting performance boundaries and impact energy utilization.

This paper seeks to briefly look back at some history for the emergence of NDE, to say something about the current state-of-the-art and its application, and finally looks at where NDE, QNDE and its various “children,” including structural health monitoring (SHM), on-line monitoring, advanced diagnostics and prognostics are expected to develop over the next decade, and may be longer.

A BRIEF LOOK AT SOME HISTORY

The integration of the effects of loading on materials, defects and inspection was, in large part, achieved through the advent of fracture mechanics, which was an activity that was greatly enhanced through the ever-improving capabilities of finite element analysis. This advance 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 to critical aircraft engine components, at all phases of the life-cycle, to design, manufacture and maintenance [6]. At the same time, other groups of engineers and scientists were considering equally challenging problems of ensuring structural integrity in the nuclear power industry [7] and in the oil and gas industries, in particular, for structures in the North Sea and in Alaska.

During the 1970s and '80s great progress was made in materials science and quantitative NDE in terms of providing an enhanced science base, 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. The range of fields of application has also now expanded into every engineering discipline. Novel integrating design approaches such as unified life-cycle engineering (ULCE) were proposed and partially applied in various forms of concurrent engineering [8]. The full power and potential of this approach was limited by then available materials science, understanding of materials degradation and response to stressors and in particular, the computation power needed to perform many of the design optimizations at a reasonable cost and within a reasonable time, and yes, in some cases a lack of vision on the part of managers and organizational decision makers.

In the 1980s and early 1990s, it was increasingly recognized that structural assessment, including quantification and evaluation of defects 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, such as cracks or corrosion, and determine a rate of growth, investigate the probability of occurrence and probability of detection (POD), and provide measurements of changes in bulk material properties caused by the aging and accumulation of damage in materials. 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, where they 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 or operational cycles [9]. NDE tools were needed to make the necessary measurements and to utilize the data in structural assessments. Others [e.g. 10] have sought to map the evolution of NDT into NDE, and much of this story, although a foundation for the current endeavors, it is largely beyond the scope of the current paper.

What Can We Learn From The Past?

In looking back at the QNDE activities from the early years there are potentially some lessons to learn. In1982 a state-of-the-art ultrasonic research system was comprised of a pulser-receiver (commonly Panametrics), a digital oscilloscope (Techtronics) and a desktop computer, with an FFT capability in ROM (Techtronics) and the output was a paper hard copy. The type of system was assembled and used by a number of research groups. An example is reported in a paper that presented the time domain responses for different sorts of flaws, and the Born approximation responses for volumetric flaws contained in flat disc. This was leading edge research and it was work that was presented at this meetings 33 years ago [11]. The classes of canonical problems that were identified at this time, e.g. single scatters in a volume and cracks of idealized geometry, have now been largely solved, even if it remains a challenge to access some of the models and data from that time period.

A second paper, of similar vintage [12] was a review of the state-of-the-art using various measurement modalities and, from my perspective more significant, a tabulation of the *Major Problems to Be Addressed*, which are reproduced as Table 1. Table 1A. presents the status and key dates for work from the late 1960's and into the 1970's, and considerers topics including the inverse Born approximation, long wavelength for scattering, eddy currents, and there is an assessment for the degree of maturity of the topic from the concept and basic science, through the feasibility, the prototype hardware and the detailed evaluation of field systems. The interesting thing from that paper, which Thompson wrote, was the listing of major problems to be addressed (Table 1B). How do you deal with the complexity of flaws, irregular inclusions, or rough cracks with closure? How do you deal with complex materials, grain and other noise, in-homogeneities, anisotropy, and complex shaped parts? How do you address damage characterization? How do you manage to move into deployment when you are faced with irreproducible beams, transducers with the same part number that don't actually give you the same beam every time? And then there is the challenge of incomplete information and ill-posedness at the heart of inversion. There was an optimism at that time that may of these challenging problems had solutions, or at least the uncertainty could be bounded, and this technology could be developed in a few years. Much progress has been made, but a number of those problems are still with us today, and the solutions remain a challenge. The lesson from this table, with the benefit of hindsight, is that the problems faced today are harder than was expected 33 years ago and that even with new types of transducers and much improved A/D and powerful computers, new approaches and insights are still needed to provide the data required to solve many real-world NDE problems, and to provide approaches that can give the data which are needed for reliable remaining safe life or prognostics estimation.

NDE/NDT TODAY

Moving forward to today: NDT and NDE are impacting the working life of many engineers and this field of endeavor is being called by an increasing array of names, including in-service inspection (ISI) which is evolving into structural health management (SHM) and prognostics. The prediction of remaining safe or service-life, is becoming a family of models, with the science and measurement technology tools, that are being used in integrated life cycle management and much of this capability is becoming a statistical or risk based methodology.

TABLE 1: Scope and status of NDE at the end of the first decade of the QNDE program and meeting (a) key dates for technologies and advances; (b) Major problems to be addressed. [after 12].

	EMATs	**Inverse Born**	**Long Wave Scattering**	**Eddy Currents**	**Stress Detection**	**Microscopic Damage**
Concept and Basic Science	1967 Spiral Coils	1974 Science Base 1976 Inversion	1974 Science Base 1976 Inversion	1975 Science Base	Various Efforts Throughout 1970s	Presently On-Going
Feasibility	1972 Gas Pipelines	1977 Spherical Void	1976 Crack Stress Intensity Factor Theory	1976 YIG Spheres Microwaves	Presently On-Going	
Prototype Hardware	1976 Gas Pipelines 1980 Projectile Systems Tube System Railroad Rails	1980 Test Bed 1981 Digital Ultrasonic Instrument	1981 Digital Ultrasonic Instrument	1981 AF Advanced Probe Program		
Detailed Evaluation	1980-1981 Various Commercial Problems	1981 Turbine Flaws Rotor Bore Composite Voids NDE Module	1979 Ceramics 1981 Machine Damage 1981 Welds			
Field Systems	Present Various Commercial Problems					

(a)

<u>Major Problems to be Addressed</u>

Complexities of Flaws
- Irregular Inclusions
- Rough Cracks with Closure
- Non-elliptical Cracks
- Multiple Flaws

Complexities of Materials
- Grain & Other Inhomogeneity
- Anisotropy

Complexity of Part Shapes
- Interfering Signals from Surfaces
- Limited Angular Access
- Curvature Effects

Nonidealities of Instrumentation
- Irreproducible Beam Patterns
- Finite Bandwidth of Transducers
- Nonlinearities of Electronics
- Digital Errors

Incomplete Information
- Ill-Posedness of Inverse Problem

(b)

NDT, the family of *testing methods that identify defects without damaging the* material, are now based on mature technology with an annual global test equipment market that was estimated at approximately $1.4B in 2011. These sales are expected to pass $2 Billion by 2016 [13]. It is also an industry that is characterized, at least in its practice, by codes and standards, by a reluctance to adopt new technologies. The applications of NDT are growing significantly and the community is challenged, in developed countries, by the inspections needed to maintain an aging infrastructure.

In manufacturing there are a lot of challenges that result from the adoption of new materials. It used to be that engineered systems mostly used steels or aluminum and they were, at least to a first approximation, isotropic and homogeneous, except when the properties went nonlinear! Now there are new materials and manufacturing processes, including in many cases composites or additive manufacturing and this is bring very large changes in the requirements for the global NDT/NDE market. With the migration of manufacturing, particularly to Asia, there are many countries now where NDT or NDE is starting to be developed and deployed for high technology products.

In looking at the needs and the state-of-the-art there are major R&D and application challenges that remain. NDT and NDE are not going out of business, and all the research has not been done. In terms of the global market there are needs that have been identified in advanced manufacturing, petrochemical, aerospace, automotive, power generation, and the globe market is seen to be growing in regions such as Asia and South America. To enable the underlying research and the application of NDT/NDE this technology is highly diversified, and there is a lack of skilled manpower. People with the necessary education and training has been identified as a *burning issue* for the NDT market in future days and that ranges from the technician side with certification, who perform a lot of the practical hands on implementation, to the research community which is represented at QNDE meetings [14].

A view of NDT for composite aerospace systems, that has been attributed to Dick Bossi (2012) is:

- Today – it is XYZ manipulation and C-scans
- Tomorrow – it will be robotics
- Future - it will be on-line Structural Health Monitoring

Looking at this view in a wider context, we have the present technology which still tends to be handheld equipment that now provides a data record and, which can, in the extreme, be the person on a rope on the side of a structure, or in a confined space where it is hot, humid and in some cases radioactive. Rudimentary automated scanning is being utilized, but this tends to be the traditional C-Scan and some XYZ capability, and the systems lack flexibility. Transducers, such as those used in ultrasonics, are much improved, and phased arrays are seeing much more use.

In terms of trends of limits to NDT, quite simply effective deployment can be the challenge. Placing a person 10's of meter up in the air on the end of a rope, in a chemical plant or on a wind turbine blade, or in a hot, noisy or confined space, or locations with distractions, most probably does not achieve the best probability of detection (POD). Just getting the job done as quickly as possible and in some cases preservation of life may be an inspector's higher priority, rather than ensuring reliable inspection POD. More attention is needed with regard to the probability for the largest defect missed, the reliability and repeatability of inspections and a improved ways to give a permanent record.

Robotics is seen as the deployment modality for the future, which can address some of the flexibility limitations of XYZ scanning. There is then the challenge, that at least the best Level III inspectors can achieve amazing performance (on a good day) in terms of sensitivity, which is better than many automated systems. Robots are now being deployed in some manufacturing environments and the economics are becoming increasingly attractive [15]. Automated and robotically deployed NDT is definitely increasing for a variety of application areas.

In some industries, in particular those where composites are being adopted, it has been said that it is all moving towards structural health monitoring (SHM), at least from an aerospace perspective and it will be testing/monitoring using continuous data gathering and real-time data evaluation. Some bridges and prototype systems are already demonstrated and deployed. Examples can be seen with the Indian River Inlet Bridge[16] and Blackhawk helicopters [17], but sensor integration, reliability, deployment and both data and systems integration remain a challenge.

Moving from engineering and deployment to research, the NDE R&D landscape is also changing. For example the Office of Naval Research has published RFP's fairly recently. One was titled, "Nondestructive Evaluation, Prognostics Fatigue Fracture and Damage Detection" and the second was "Nondestructive Evaluation, Prognostics Advanced Sensors and Technologies." NDE is moving to be more than measurements, it is including remaining life. In terms of what people are wanting and paying for the research topics are changing but major needs are still there, and they are increasingly interdisciplinary and challenging.

NDE and Materials Science

To enable a more quantitative science to be developed there is a merging between NDE and materials science. Traditional NDT has focused on the measurement part shown in Figure 1. Looking at structural health and remaining life the activities are moving to the right, with much more interest in microstructure parameters, determination of material properties and then predicting structural performance. There is also the interaction between properties, structure and performance which interplay in design, and then manufacturing and QA/QC.

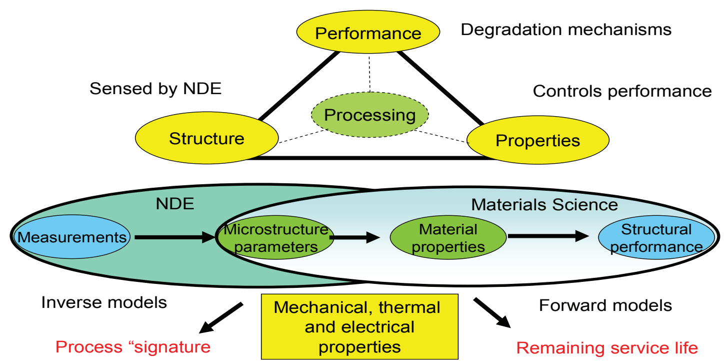

FIGURE 1. NDE and Materials science [1].

Based on NDT/NDE measurement data which gives the microstructural "signature," there is, looking back in time, a process signature and if you go forward in time, it gives the data for models which are employed for remaining service life and prognostics, usually within a statistical framework. Ultimately NDE is involved in the measurement of mechanical, thermal and electrical properties, or measurements that are dependent on these properties and sample morphology. For example, for ultrasonics measurement provide a signal amplitude, a voltage, that reflects spatial and temporal characteristics of a physical acoustic responses (scattering, attenuation, absorption), which can be a function of frequency, and the velocity and attenuation data, which is convolved with measurement system characteristics [1]. Such data are converted to represent a feature signature most commonly using imaging or a discrete scatterer inversion algorithm. The NDE derived data are then considered in the context of system performance, and potential stressors and degradation mechanisms. In these analyses NDE is getting pushed back into the early part of the life cycle. It is becoming more like process monitoring and it is being used for process monitoring and control. Without such measurements for composites and ceramic-composites, you can make very expensive scrap. If you make an item from a piece of steel, if it is wrong you can throw it back in the pot and recycle it quite easily. A lot of the composite materials don't recycle easily or in some cases at all.

With the fusion between NDE and process monitoring, measurement and control there is the increasing need to provide measurement of material properties, together with correlations between desired material properties and parameters that can typically be monitored using NDE measurements. Nondestructive measurements of mechanical properties remains a holy grail [18]. There is an increased overlap between what has been seen as materials science and what has been considered to be NDE, in terms of both measurement scale, and property monitored. The effects of material phenomena, such as texture, applied stress and temperature on the *measurand* (measured quantity) are complex [19], and in many cases an initial or reference state is hard to access. Some of the properties of interest and conditions which impact them have long been known and they are listed in Table 2 [after 20]:

Degradation Mechanisms

In looking at changes in material properties during service, in general terms aging and degradation mechanisms are classified into two broad classes. Internal phenomena where there are changes to microstructure or chemical composition or there are changes in intrinsic properties, due to phenomena such as thermal aging, creep, or irradiation damage. There are those phenomena which result from imposed stressors, that cause physical damage to the component, and this can include metal loss due to corrosion or wear, others that cause cracking, in one of many forms or deformation due to excessive loading.

TABLE 2: Mechanical properties of interest and parameters which can which can be measured [after 20].

Mechanical Properties	Measured Parameters
Tensile modulus	Anisotropy
Shear modulus	Microstructure (morphology)
Tensile strength	Grain size & distribution
Shear strength	Porosity, voids
Yield strength	Phase & chemical composition
Bond strength	Hardening depth
Hardness	Residual stress
Impact strength	Heat Treatment (from surface depth)
Fracture toughness	Fatigue & other forms of damage

The phenomenon encountered in aging related degradation are complex and require sophisticated, state of science and technology procedures to effectively monitor and manage the effects and to ensure safe and reliable operation. In these situations not only technology that is involved. There needs to be an effective management system in order to correctly implement both the monitoring and appropriate mitigation actions.

NDE, Materials Characterization or both?

Traditional NDT has sought to detect and then locate and size a flaw, and to ask the question, what is the smallest flaw detected? It is more important to ask what is the biggest flaw you will miss in this part, with this inspection and what is the POD? From materials characterization this has sought to provide underlying properties, including characteristics such as the form of the microstructure, a metric to describe grain size and what are parameters such as moduli.

In looking at life estimation there is interest in ensuring no significant defects, and also some metrics or signatures, as well as providing moduli that relate to performance. Such materials characterization is seen as becoming much more important to the reliability and the safety. In some cases, the first crack is catastrophic. In many cases 95%, or more, of the life of the part is expended before the first significant defect forms that is detectable by traditional NDT. There is the need to investigate the detection of precursors, and to understand the progression of what can be seen as subtle changes in properties and data. This, in most cases, requires quantification of an initial material state. In the case of ultrasonics the signals of interest are those usually considered to be noise: the random scatterings from the microstructure which is attributed to the inhomogeneities within a metal. Useful tools that provide for grain signatures are being developed [21] and signatures established that relate to quality.

The need is to be able to assess the progression of damage *before* cracks form, to provide quantification of the initial state and check for evolution of damage when possible, and to provide for validation of prognostic projections. There becomes a need for microstructural characterization tools as well as flaw detection tools and this is a key ingredient in development of state awareness strategies. The place of micro-structural characterization is shown in figure 1, in the progression from measurements to structural performance. The challenges in moving from NDE measurements to integrate this aspect of characterization are not trivial. Each link in this process has its own challenges. There are issues on non-uniqueness, inadequate sensitivity of measurement modalities to key parameters and limitations in the basic theory which force the adoption of a stochastic approach. The remaining challenge is to achieve required sensitivity and then to design, develop, and evaluate advanced laboratory NDE techniques to quantify precursor state, validate theories on precursors and demonstrate potential for field deployment. There is a further issue, this relates to mitigation. Can actions be taken to remove or modify stressors so as to reduce the rate of material degradation? Can changes be made to operating or material conditions which can enable a part to have a longer service life?

Assessment of NDE Tools for Potential for Degradation Characterization

If NDE is to look at degradation before discrete larger cracks are formed, and enable mitigation to be implemented, a different assessment of method potential is needed. Some years ago Lemaitre and Lippmann presented a table that considered 8 NDE methods and 5 classes of damage. In each case a damage metric is given showing a functional relationship between damage and degradation. The different sensing modalities were then graded for specific applications. [After 22]. A recent IAEA cooperative research program project has revisited this topic and provides an assessment of the issues and the challenges which are still faced [23].

TABLE 3. Potential for NDE techniques for detection and characterization of various material degradation precursors, and proposed damage metrics. (Where *** graded best, ** OK and * some capability)

Damage		Brittle	Ductile	Creep	Low cycle fatigue	High cycle fatigue
Micrography	$D=\frac{\partial S_D}{\partial S}$	*	**	**	*	*
Density	$D=\left(1-\frac{\bar{\rho}}{\rho}\right)^{2/3}$		**	*	*	
Elasticity Modulus	$D=1-\frac{\bar{E}}{E}$	**	***	***	***	
Ultrasonic Waves	$D=1-\frac{\bar{V}_L^2}{V_L^2}$	***	**	**	*	*
Cyclic Stress Amplitude	$D=1-\frac{\Delta\sigma}{\Delta\sigma^*}$		*	*	**	*
Tertiary Creep	$D=1-\left(\frac{\bar{\varepsilon}_p^*}{\bar{\varepsilon}_p}\right)^{1/N}$		*	***	*	
Micro-hardness	$D=1-\frac{H}{H^*}$	**	***	**	***	*
Electrical Resistance	$D=1-\frac{V}{\bar{V}}$	*	**	**	*	*

NDE A Full Partner in Product Development

In product development there is a need for NDE to become a full partner in design and development. In this framework there are four M's, materials, manufacturing, measurements, and models. The choices relating to each of these need to be fed into the process models, the performance and stress analysis models, failure models, the reliability models, the inspection performance/POD models, the cost analysis, and in many cases a 3-D visualization involving CAD and a multi-physics analysis. This is not what an ASNT Level 3 typically does. This is what a professional engineer does. There is a need to try and build bridges between the engineering community and the traditional inspection community. There is a need to have a concurrent approach to product development and wider adoption of unified life cycle engineering (ULCE). That is not a new idea, some companies are implementing this sort of approach and it has been periodically presented by various people at meetings in this series [e.g. 8].

Manufacturing Metrology

There are trends to move manufacturing metrology QA/QC beyond dimensional characterization [24]. The desire is to provide fast, accurate, safe, and flexible measurement capabilities. This is all part of the trends in production/manufacturing to enable efficient resource utilization, provide flexibility, transparency and leverage new processes. When material characterization is considered there is a need to measure fissures, porosity, texture in the microstructure as well as hardness and moduli. To meet these needs there is a blending of more traditional dimensional metrology and aspects of materials characterization, NDT/NDE.

In many industries the materials employed are increasingly not a traditional steel or aluminum, it can be a composite or a powder metals. The material fabrication, forming and jointing can involve new manufacturing processes, for example additive manufacturing and solid state bonding. The material "creation" becomes integrated with forming and this presents new challenges for measurement and sensors which may involve harsh environments such as a high temperature, shock or vibration, and as measurements are integrated into manufacturing, they are looking more like on-line monitoring for process control than conventional NDT or NDE, although they use the same measurement phenomenology.

In the new advanced manufacturing environment you can no longer have an NDE evaluation where you throw the part "over the fence" when built. Metrology, in all its forms, has to be designed into the process if it is going to be effective and provide products with a good and extensive life. All of this moves the necessary metrology beyond current NDE implementations, to be more in the form of processing sensing for QA/QC, and outside the realm of experience for most NDT practitioners.

Allowables in Materials/Composites

The changes in materials and processes requires changes in thinking, particularly for composites. In a particular design, the scale and degree of variations and indications that will not cause a de-rating of the design performance are termed the "allowables," short for acceptable variations in composite or other material structure and properties. The effect of imperfections on the stress-strain relationship for a materials is illustrated with Figure. 2. For a *perfect* composite, the properties are optimized and in the top right-hand corner when it comes to the stress strain relationship. In reality the properties that you can utilize move towards the left and down. This loss of performance is related to a variety of features including, surface irregularities, splicing, weaving, inclusions, voidage, damage, and binder pockets. In relating properties to inspection there needs to be a mapping between what is measured with NDE and its significance.

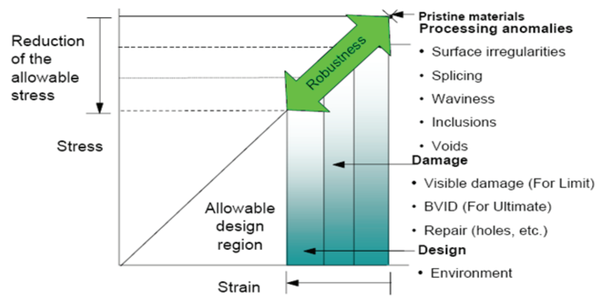

FIGURE 2. Allowables in composites.

Such quality and inspection costs impact the size of the resulting allowable in a design region. The nature of defects encountered in composites can for example be fundamentally different. In a metal the issue may be a discrete crack, in a composite it may be some zone or volume of poor consolidation, resin rich or light in the mixture, all of which impact the measurement methods, detection, data analysis and the models that use data for life estimation.

In terms of measuring quality these can vary by application. In terms of an example, if you want a cheap wind turbine, then you want cheap wind turbine blades, but they still need to meet performance requirements. A manufacturer would really like to have aerospace quality materials in the blade, however aerospace quality composite is somewhat more expensive, than relatively cheap composites currently used for wind turbines. If you are going to optimize the design and get the maximum power out of the wind turbine blades, it needs a better quality composite, higher strength, and effective jointing that is cheap and can be inspected cost effectively. All this relates to an understanding of the allowables at manufacture.

In service it is then necessary to understand service damage with impacts, degradation of joints, micro-cracks, and pores in-service. As a result allowables, particularly for composites, have to become much more a part of our NDE, data analysis, and the life cycle analysis with the discussion of how real and significant defects are detected from among the noise of all of this natural structure, the surface waviness and other irregularities.

LOOKING FORWARD

Jeremy Rifkin has written about what's being called The Third Industrial Revolution [25]. In his vision for the future you have solar, wind, and hydro-geothermal as major energy resources. To this I would add nuclear power and some of us like small modular reactors. This vision for the future is more than just looking at energy resources. From the US perspective there is an interest in returning manufacturing here. This will not be traditional heavy industry. It will involve new high technologies, using new materials, and new fabrication processes. Such a change brings new opportunities. Just one example: if you are employing additive manufacturing the final product can be un-inspectable. For such a product do you assume that process control will be adequate to ensure quality? How do you put your NDE into additive manufacturing as process monitoring?

New materials bring new aging issues. For a mostly composite aircraft, how do you deal with new aging phenomena? How do you deal with a Boeing 787 where the ground equipment gets banged against the side of the plane? How do you know quickly and effectively, on the flight line, ensure that you haven't got hidden damage? What data is needed to enable a fly or no-fly decision to be made?

As we move into facing new challenges with materials and these may not be just the traditional fiber-reinforced composites, they may be ceramic components, and a lot of other new things are starting to come in. There is a market for the new materials and the manufacturing processes, which are all going to need significant NDE. With new materials how do you get state awareness and how do you get life prediction for new materials?

Where are we trying to go again? Dr. Mike Farley [26] mentioned there was a drive earlier on to detect smaller flaws, enable life extension and retirement for cause. With composites people are now trying to better understand the physics of inspection. Conventional traditional NDT is giving real features in C-scans that show structure, which may be of no degradation significance. There are many examples of the types of natural variability that can be there and which is seen at inspection. There are opportunities to use model-based approaches to simulate such "noise" and hence evaluate inspection methods for inspection potentially. If you're going to try and cast metal or form composites with artificial flaws, it's expensive and challenging. In looking a real parts hopefully you don't get sets welds and surface structure that will drive you crazy when it comes to inspection. It's expensive to produce lots of samples needed for a performance demonstration. To use models for performance demonstration/MAPOD (model assisted POD) the models need to have the physics to be right, and they need to have been validated.

A Changing Landscape--Money and Life Consumption

People are getting much more interested in this thing called *money* and component life, rate of consumption and remaining safe life. This is increasing interest in prognostics and methods to measure how much remaining life have you have. For example US nuclear power plants were designed and initially licensed for 40 years, and many are now going to operate for 60 years. There is discussion can you go out to 80 years? That is going to require interesting additional information gained through ISI/NDT, monitoring, diagnostics and prognostics. It's the same for the aging military aircraft problem. The civilian aging aircraft problem in developed countries has vanished. Part of why Boeing and Airbus are doing quite well is because, at least in most western countries, airlines have bought new aircraft. Part of this relates to fuel costs and efficiency, and part was to eliminate old aircraft. For the older aircraft in the military, they are trying to do life extension.

There is a slow move towards including NDE in the design analysis. You perform a stress analysis and stick these materials together. And then, oh, you have traditionally asked how do I inspect it? The community needs to move to a point where the NDE engineer, or at least an engineer with adequate NDE knowledge, has the needed analysis tools and is a recognized professional who will be sitting at the table and is in a position to say to the lead designer, "perhaps it's not a good idea to design it that way, if you ever really want to inspect it." Design for testability is one of the major issues that is not being done. Some companies are beginning to get the message and they are realizing there are advantages to actually design for inspecting.

GAPS AND CHALLENGES

The inspection models are still limited in capability and use. Model based approaches are being adopted but work is needed to enable analysis for design for testability to be as common place as a stress analysis using a finite element code. Review for POD, using models needs to be more commonly employed.

Manufacturing metrology is expanding to include inspection for defects, pores, as well as texture, and mechanical properties. NDE methods that provide such properties as hardness, and moduli remains a holy grail for NDT. There is a general need for accurate, fast, safe and reliable NDE measurements that can be integrated in to manufacturing processes.

If one considers the example of the evolution of stress corrosion cracking, as shown in Figure 3 [after 27], which shows NDT limits that are applied to inspections where you find a defect and then fix it. More proactive methodologies are being developed. Traditional NDT works in the phase 5 of the life cycle. NDT works really well when you've got a big enough crack and this is where linear elastic fracture mechanics works. Once a crack starts to grow, it can really be predicted quite well if you know the stressors. However, 95% or more, of the life of the component is before this phase in degradation. There is a need to push back measurements to the left and understand what is happening when you start to get some chemical phenomena, some stress phenomena, something that's really happening below the traditional NDT limit. In Phase 1 the materials scientist has a variety of tools, but it's problematic to make measurements between phase 1 and phase 5.

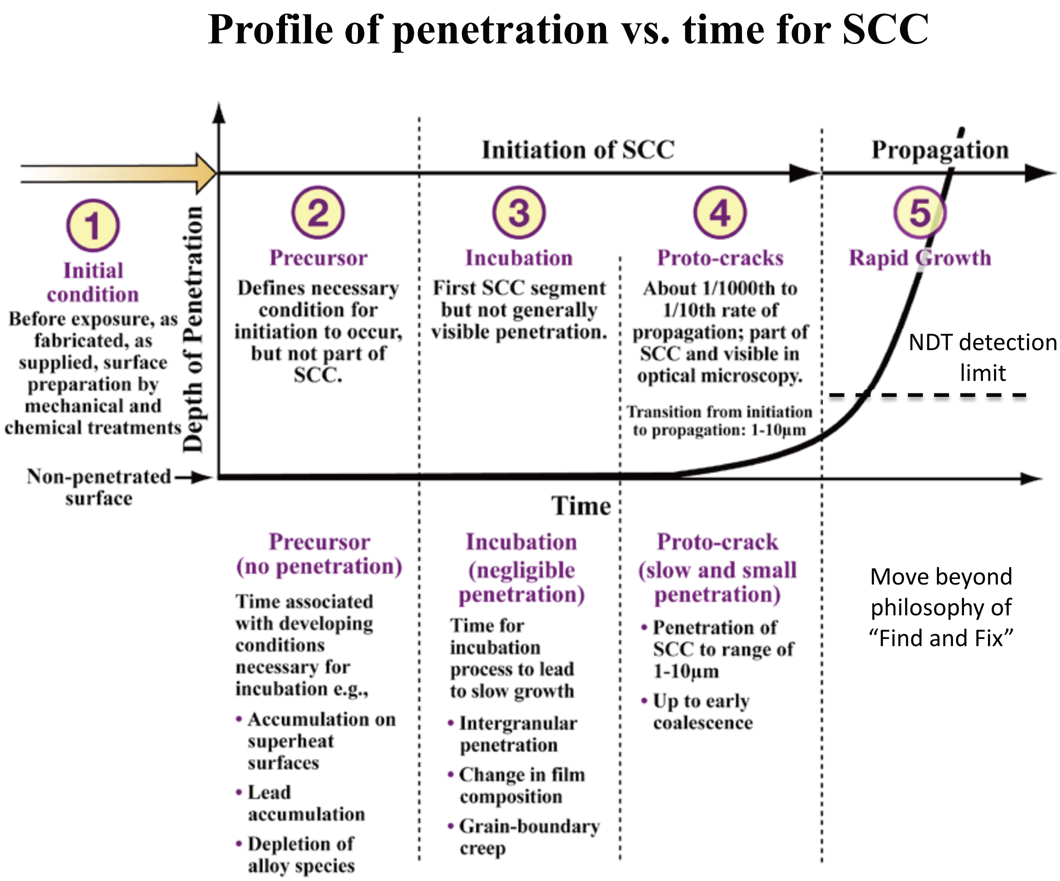

FIGURE 3. Evolution of damage – stress corrosion cracking (27 after Staehle).

There is a need for much more to understand the mechanical failure progression. In looking at failures there are the materials, the components, and the sub-systems. Analysis does remarkably well in the laboratory at the materials and component level. To predict where things are starting to fail at the system level, before "water on the floor," is in many cases really challenging. There is a need for better understanding that failure is a process, not a specific event. The higher up the hierarchy you come, the harder it tends to become and the less manageable it remains as you start moving to the right because this is when really bad things start to happen.

If you look at some examples of stress or assessment in various stage, in track nucleation, there are no show stoppers. For example you can use ultrasonic backscatter to give materials signatures for a variety of applications on turbine discs. This can be remarkably good and signatures can be demonstrated and correlated with life. When there is degradation there are measurement methods such as harmonic generation for short cracks, nonlinear phenomena, which Larry Jacobs mentioned [28]. There are some challenging measurements from an Air Force perspective and you want to do it on the wing, but in principle, you can do it in the lab. When you start looking for long cracks, again, the challenge is not doing it in the laboratory, it's the challenge of actually doing it on a flight line. So there is a need to move more to a material state awareness [29]. There is a need to determine degradation effects on the rest of the aircraft and predict early, the further back into the early life cycle where you see changes, the better you can do in terms of system management. The desire is to have advanced sensors and detection techniques that can see an incipient fault almost before it develops.

There are changes in the technologies that are being used. In ultrasonics these increasingly include ultrasonic phased array, and time-of-flight diffraction. A phased array has moved out of the laboratory to now be a standard piece of equipment, which is available at a reasonable cost. This gives a permanent record and this, together with changes in codes, is really changing what one can do. For the permanent record of an inspection one no longer has to relying on radiography and the ultrasound can give you a 3-D data set as the permanent record. The challenge then becomes the size of the data set to process. Large datasets, both 3-D ultrasound and computed tomography are becoming large, examples can easily get to 60 gigabytes and up to terabytes. Simply recording and displaying, let alone manipulating and processing such data in a reasonable time is stretching computational resources. The advent of parallel processing and GPU's are adding new capabilities, which reduce computer processing times by several orders of magnitude, but simply the computer science aspects of these challenges remain a work in progress.

Another area where there is much activity is modelling. There are an increasing range of codes that range from the research code to the large commercial packages, such as CIVA. These can be used to model ultrasonics, x-ray, eddy current, and thermography. Reviewing the various models has been included in several sessions in this meeting series. The various codes all have their strengths, they all have their limitations, but modelling has become much better, and validations more comprehensive, at least for the commercial codes. There remain research opportunities to provide better or complete models for POD estimation. There is the need to understand what the detection limits are, what the lower confidence bounds are, and do a better job of educating the designers in where POD is really sitting, and modelling tools which are easy to use by engineers who are not professional modelers are still required. Model-Assisted POD clearly combines the knowledge of a lot of elements of this: the inspection physics, the reliability. Understanding not just the probability of detection but the probability of miss, particularly in noisy environments, is an area where there are still challenges and opportunities.

An emerging area is prognostics, particularly for structural materials, and the characterization of early damage. This area requires better modeling and integrated modelling tools, as well as novel measurement insights.

Motivation for NDE of Structural Health Monitoring

Conventional NDT is remarkable effective at characterization of local macro-damage, particularly when applied to systems with a leak-before-break design. This assumes that you know where to look and that you have access. Traditional or conventional NDT methods (as described in many codes and standards) can be challenged when you have large areas to inspect. If you look at the example of a large bridge, an aircraft, or a pipeline, how do you find degradation of some "global damage," which is only significant when its presence throughout the item that is considered. It is necessary to provide quantifiable and automated methods for covering large areas. Small local C-scans for ultrasonics, or similar data from other techniques, and basic penetrant inspections on a component can be remarkably effective, but large area coverage is a challenge. Some progress is being made with robotics for components such as aircraft skin and wind turbine blades, and the economics is improving.

The community is moving towards SHM and prognostics and large failures need to be avoided. Failures in wind turbines and those such as the Aloha jet need attention to focus on early damage. There is an increasing need for inspections to support life extension so as to maintain legacy systems. The challenge can become the frequency of inspection. You can end up having to perform inspections so often that it simply becomes cost prohibitive. The result is that there are moves towards condition-based maintenance philosophies, on-line monitoring and diagnostics, but retrofitting on-line monitoring can be both technically challenging and very expensive.

Jan Achenbach in what I think was a Stanford 2008 talk has said that you've got NDE and structural health monitoring and prognostics, and that it's not just NDE or SHM, you've got to bring the two together. SHM has limited coverage, and you've got flaw sizing and detection methods that has yet to have acceptable POD demonstrated, so you're really trying to bring together and fuse data from these two approaches. You need to perform traditional, periodic NDE as well as implement appropriate on-line monitoring. You can't take 100,000 sensors and put them into an aircraft or a nuclear power plant. You have to be smart and use the limited number of sensors to tell you where to look for the periodic inspections, so as to give you the confidence in a whole life management philosophy. You've got a variety of prognostics algorithms, they are not magic. They range from those where there is statistical life algorithms where they are very general to a class of problems to a physical model on a particular system, with dedicated sensors and data collection and analysis. The latter is more expensive with higher confidence and the former cheaper and more generic. Bayesian algorithms are a part of these approaches, as are model-based probabilistic methods and neural net systems. There remains the need to bring together some automated prognostics systems and that operates long-term and has needed sensors, and data to integrate with that from stress models which can all feed into life estimation algorithms. If one could simply execute the strategy of understanding the initial state, the damage progression, the damage state, and the failure model, and make the needed measurements one could predict expected life. It would be a done deal. Even for a moderately complex system, there is an awful lot you need to know. What is missing? We don't currently determine the initial state of a component with high enough precision. If it's a legacy system, it was built 40 years ago. If it's a pipeline, we may not even know who was the manufacturer of the pipe was, and what is in the ground in front of you now. We've not traditionally monitored the operating environment. We don't understand the stressor environment. We don't have good enough damage progression models. They've been traditionally more empirical. Uncertainty, there is huge uncertainty in the data and there is huge variability.

WHERE IS NDE GOING?

So where is NDE going through the next decade to the 50th QNDE? I think it is reasonable to say that NDE will grow in its application. Beyond this where is the future, where is my crystal ball going to take us? There are drivers for quality, there are drivers for safety, there are drivers for sustainability and many would say, the biggest driver of all is cost of ownership. We've got to enable better and more effective deployment of traditional and advanced NDE. Many of the techniques are going to be talked about in this meeting. We have to deal with large data, permanent records. We've got massively better equipment, computer technology has helped us amazingly. They went to the moon with 64K of RAM. Almost anybody with any computer device, 64K of ram is ridiculous. You've probably got a memory stick with at least 2GB on it and 64 GB is common place. We've got better equipment, automation robotics, we've got some integration into manufacturing. We're going to be looking into full characterization and a merging of the basic science with materials science and design and the increasing use of models.

There is a need to enable better and more effective deployment of "Traditional and advanced NDT." This presents challenges in terms of large(er) data sets, a requirement for permanent records, both the need for and opportunities provided by better equipment, opportunities for automation and robotic systems. There are needs and opportunities for some integration into manufacturing process monitoring measurement and control, but these implementations are challenging to sensors. There is a desire to better characterize material state and mechanical properties, with a full characterization, being a merge into materials science and design and all facilitated through an increasing use of models.

The needed R&D is going to be harder. There is a need to learn from the past and what have been done over the past four or five decades. Too much research is ignoring past work, which may be because it is not known, and it is not all easily accessed through Google! NDE is going to be seen as part of condition-based maintenance prognostics and manufacturing processes. There is a need to move beyond traditional or conventional NDT and for methods to become more quantitative and more sensitive. New sensors are needed and the measurements need to be integrated into manufacturing metrology. Tools for early damage characterization are needed. There is a need to move from SHM to true prognostics. NDT is going to be used to minimize the cost of ownership and it needs to be integrated into engineering product life cycle design. Design for inspectability and monitoring is needed.

One fundamental area is quantify uncertainty from measurements to defect characterization. There are a lot of ill-posed problems. One roadmap for prognostics that is out there and which came from DARPA, shows a wide range of topics that are still needed to give real-time operations, self-healing systems and fault accommodation. That is one vision of the future to predictive prognostics and advanced NDE is just part of a much wider range of activities.

CONCLUSIONS

NDT is a mature industry, with global equipment sales fast moving towards $2B. per year. The use of NDT and NDE can be expected to increase, but there more advanced problems are getting harder. NDE must be seen more as a part of the wide field of engineering, as an interdisciplinary endeavor, that brings together the expertise of materials science, metrology, with the underlying physics, as well as statistics, computers, robotics and software. The use of conventional NDT will grow in developing countries and in developed countries the challenges will include those associated with maintaining aging infrastructure. The adoption of advanced manufacturing, will require new metrology tools and methods to provide data for new materials including powder metals used in additive manufacturing and various composites. For some systems the future will move to structural health monitoring.

The lessons from the past proceedings from this conference series include that the problems faced today are harder than was expected during the first decade of QNDE research. Even with new types of transducers and much improved A/D and powerful computers new approaches and more basic physics new insights are needed to provide the data needed to solve many real-world NDE problems, to understand and measure early degradation and to give the required data for remaining safe life or prognostics.

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