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Conventional NDT is a mature technology, for which there is a significant instrumentation and services market expected to reach $6.88B by 2020. NDT is seeking to become more quantitative and leverage advances in instrumentation. In addition aspects of the field are undergoing significant transition as new materials and advanced manufacturing are seeing increased usage. The landscape is further changing with moves toward structural health monitoring (SHM) and advanced diagnostics, which are bring SHM and NDE together to give complementary data, as operators are seeking to address requirements for safe life estimation, condition based maintenance (CBM) and prognostics. The limitations and capabilities are discussed including for the implementation of prognostics, together with various technical challenges in moving from NDT to prognostics.

Keywords
NDE, structural health monitoring (SHM), prognostics

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From NDT to Prognostics: Advanced Technologies For Improved Quality, Safety And Reliability

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Abstract: Conventional NDT is a mature technology, for which there is a significant instrumentation and services market expected to reach $6.88B by 2020. NDT is seeking to become more quantitative and leverage advances in instrumentation. In addition aspects of the field are undergoing significant transition as new materials and advanced manufacturing are seeing increased usage. The landscape is further changing with moves toward structural health monitoring (SHM) and advanced diagnostics, which are bring SHM and NDE together to give complementary data, as operators are seeking to address requirements for safe life estimation, condition based maintenance (CBM) and prognostics. The limitations and capabilities are discussed including for the implementation of prognostics, together with various technical challenges in moving from NDT to prognostics.

Keywords: NDE, structural health monitoring (SHM), prognostics.

1 Introduction

Nondestructive testing (NDT) is now considered to be a mature technology with a total market including both equipment and services, which was estimated to generate revenue of $ 3.77 B in 2013 and is expected to reach $6.88B by 2020 [1]. Recent decades have seen a move from NDT to consider nondestructive evaluation (NDE) and now advanced diagnostics, material state awareness (MSA), which seek to give materials characterization in addition to defect detection and structural health monitoring (SHM), together with prognostics, to predict remaining safe or service life. Many consider NDT and the various related assessment methodologies to be expensive: no - it is the failure to ensure a high quality product and monitor it in use, including the use of inspection, which is expensive, particularly when considered in terms of the management of life-cycle costs, liability, safety and reliability.

Over the past 40 or more years there has been an evolution, and many would say a revolution, in NDT and its implementation, with the emergence of the more quantitative nondestructive evaluation (NDE), needed to provide data for fracture mechanics and other tools, and now advanced diagnostics and prognostics. These modalities are just part of wider quality assurance/quality control (QA/QC) programs at manufacture and then product life cycle management approaches, which can include SHM and CBM [2]. When value propositions are considered QA/QC on finished products is, in many cases, just too late in the process. Particularly for high value parts with high fabrication/machining or other process costs, there is a need to reject defective parts as early as possible, to save energy, materials and to potentially enable material rework or reuse. As advanced manufacturing methods, including the use of powder metals and composites, are adopted there is, in addition, a need to use NDE to identify and define bounds for the process parameters that must be controlled to obtain high quality parts.

As modern design tools and materials are enabling products that have narrower design margins on materials, in terms of weight, thickness and strength, there is a growing interest in migrating from periodic inspections to various forms of SHM, and towards the integration of data in advanced diagnostics and in some cases prognostics. The need for SHM is also being driven by an increase in need for life extension and maintenance of high value legacy systems, such as bridges and energy infrastructure (e.g. nuclear power plants and pipelines).

It is also being found that periodically applied conventional NDE methods are being challenged by the needs of aging systems. For example many older pipelines in developed countries, which may date back to the 1950s, were never designed for in-line inspection (ILI) tool deployment. For other infrastructure the frequency of inspection and inspection technology needs require review in light of known and emerging/unknown degradation mechanisms, which can occur as a unit ages. Such challenges have been found with legacy nuclear power plants. There are opportunities for O&M savings in moving from on-time to condition-based maintenance (CBM) philosophies, including also on-line monitoring and diagnostics. The predictive/prognostics methodologies can in addition

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help to reduce operation and maintenance (O&M) costs, including avoiding unscheduled down time and enabling more effective scheduling of maintenance, rather than managing in a more reactive mode.

2 Limits to NDT/NDE

There is a need to move NDT beyond a workmanship standard at fabrication and in-service inspection philosophy of “find and fix” for defects. Life management needs to become more proactive in terms of component management, moving into condition based maintenance and prognostics.

In seeking to understand the factors which limit the performance of NDT and NDE significant analysis can be required, particularly if seeking to quantify performance. At the heart of NDT is the physics of fundamental energy-material interaction. This can involve almost any form of energy including heat, light, electromagnetic waves, sound/ultrasound or ionizing radiation. There is then the instrumentation employed. This is typically comprised of a sensor, energizer/receiver system, and now in the vast majority of cases some form of computer based data recording and display, that can be coupled to a scanning or other mechanical manipulation capability. Such systems have limits set as the sensor responds to an analogue signal which is then digitized. The sensor has characteristics needed to enable a particular inspection to be performed. NDT is treated as its own area of activity, but it is also just one implementation of measurement science (metrology) and much of the good practice for making measurements and treating data apply. For an ultrasonic system it will involve wave generation and the parameters which set the beam characteristics. The key parameters will typically include the transducer frequency, its diameter and its bandwidth, which function with some sort of pulse excitation. The inspection technique, in made cases, set and performed in accordance with a code or standard, which has criteria defined with regard to detected detects. There are then the human factors, which are more significant, for a manually scanned transducer, but can still impact performance even when a mechanical scanning or robotic unit is employed.

Fundamental to any NDT technique is understanding the material to be considered and ensuring that the inspection modality is appropriate to properties addressed (i.e. ultrasonics, material density and the elastic moduli, which combine to determine velocity). There is then the issue of the type or types, shape and size of defects, which all need to be considered in the context of the base material properties including grain size and the component size, geometry and applied stressors/loading [3]. One example of how for a compression wave and a simple defect/cavity, the response changes as a function of feature size and frequency. This is given in Fig 1 [4]. As NDT began to seek to become more quantitative it was recognized that there was a need to: (i) improve measurement system signal-to-noise, (ii) provide instrumentation to channel the attention of an inspection to flaws, (iii) provide positive assurances that equipment is performing its intended function and (iv) automate control and program functions susceptible to human error [3].

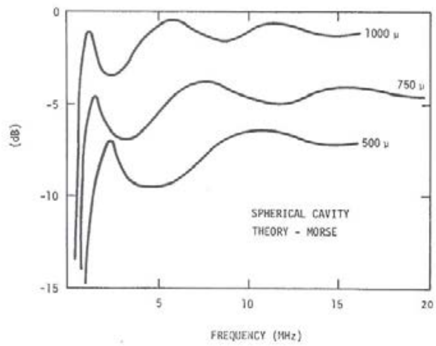

Fig 1. Theoretical reflection coefficient spherical void in titanium [4].

Modern equipment has been improved significantly as illustrated with the phased array unit with a B-scan display and position encoder shown in Fig 2 [5]. The system incorporates major improvements in instrumentation which have leveraged advances in computer technology. There have also now been several decades of work on the fundamental energy – materials interactions which have established much of the science base needed [e.g. 6]. There is increasing use of automation, but this tends to cause some loss in inspection sensitivity, at least when compared to the best 10% of manual inspectors, but it can achieve improved repeatability!

Fig 2. Phased array unit in use on a thick-wall polymer pipe, inspecting for lack of joint fusion [5].

NDT is more than just buying and using a system. The question then needs to be asked, what is it that, in many cases, still limits current NDT implementation? The biggest issues appear to be lack of NDT consideration at the design stage for a part or unit. There remain issues of inadequate engineering of the NDT technique itself. There can then be cases where the defect detection requirement is too close to the ultimate detection threshold, particularly given that there is still an expectation, as an inspection standard, to ensure freedom from defects (which actually relates to detected defects). The relationship between crack size and the typical hierarchy of acceptance criteria is illustrated with Fig 3 [7]. Such criteria need to be set using a combination of inspection and performance analysis, which includes determination of performance based part defect acceptance criteria. There then remains the impact of human factors in the inspection cycle, including lack of adequate expertise in analysis and solution development. That all being said the best of routine inspections using modern technology can be remarkably successful.

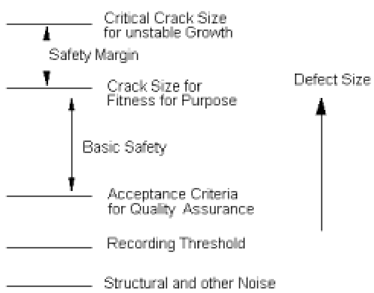

Fig 3. Schematic showing relationship between crack size and NDT acceptance criteria [7]

Traditional NDT/nondestructive evaluation (NDE) has sought to detect, locate and size flaws. There has been much focus on the smallest detectable defect. Recent years has seen a growing acceptance and recognition that it is the largest defect *MISSED* and the probability of detection (POD) or miss which is needed to adequately provide a probabilistic risk assessment in relation to assessment of part performance. There is also a recognition that it is necessary to better characterize material state, with what is being called material state awareness [8]. This involves materials characterization including mapping base properties and parameters such as grain size, including stress, strain, moduli, fatigue, and fracture toughness and the evaluate/determination of material properties prior-to and after the formation of a flaw. Probability of detection (POD) is a topic in its own right [9]. The issues of reliability, repeatability and POD and impacts of microstructure on POD have been addressed extensively by others [e.g. 10, 11].

Materials characterization is important to assessing infrastructure reliability and safety, because in some cases the first crack can be catastrophic, such as when due to zero tearing modulus. It is necessary to guide focused nondestructive testing to regions with a high propensity to fail. It is also used to provide an early warning of structural integrity prior to flaw formation, and help provide an accurate lifetime prediction. Such characterization is becoming increasingly challenging with advanced materials, and changes in processes, for example with powder metal based items, additive manufacturing. With the increased use of structural composites in products such as aircraft, designs tend to remain conservative as characterization and significance of defects may not be adequately understood. In looking holistically at this field it is seen that there is an increasingly interconnected and intimate relationship between NDT and materials science, which is illustrated with Fig 4 [5].

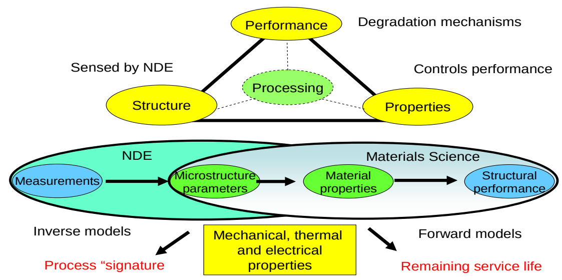

Fig. 4. Illustration of the intimate relationship between NDE and materials science [5]

3 Manufacturing allowables, defects and damage.

Advanced materials are changing the needs and implementation of NDE, particularly when composites and powder metals are considered [2, 12]. A particularly critical question for composites and additively manufactured parts is the impact of manufacturing anomalies and then, particularly for composites, damage on design allowables or manufacturing acceptable features, with criteria for types and acceptable "anomalies. Fig 5 considers the case of a composite showing the limits to the allowable design region. This degraded performance results in requirements to be conservative in the design of parts and this typically increases the quantity of material used and hence weight, which in aerospace applications impacts fuel efficiency and performance. An equivalent figure for a powder metal part can address the assessments and limitations imposed through the QA/QC process in the steps in manufacture from the powder through to the finished part [12].

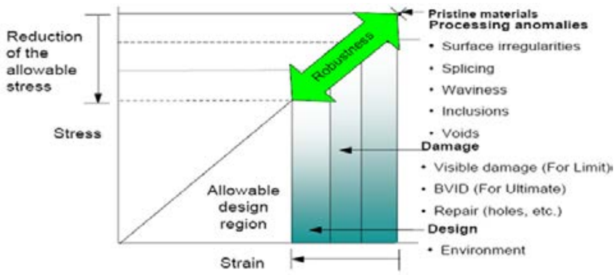

Fig 5. Schematic showing impact of both design anomalies and damage on a composite

The next issue is then the evolution of damage and the challenge of what and when degradation can be detected in-service. A schematic for the example of the evolution of stress corrosion cracking developed by Staehle, is shown as Fig 6 [13, 14]. Probably 95% of the life of a part is in phases 1-4. It is only in phase 5 when there is relatively rapid growth that NDT can usually be expected to find the cracks. Tools for early detection of aging/degradation are of growing significance. There is a gap in technologies between those used in the laboratory for materials science and those which can be used for NDE in-service.

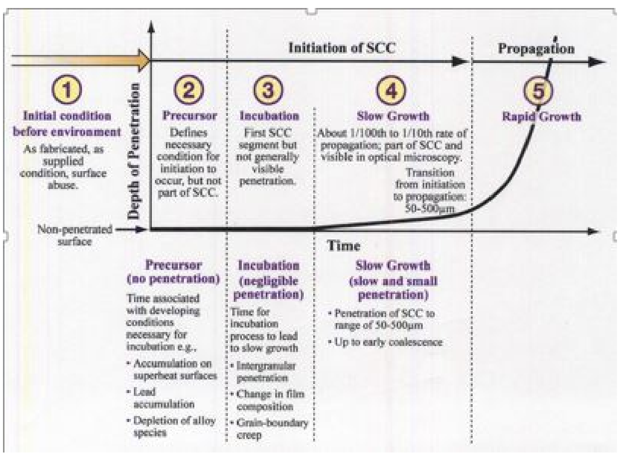

Fig 6. Evolution of stress corrosion cracking [13, 14]

The phenomenon of aging degradation are, in general, complex and its understanding and analysis requires sophisticated science and technology procedures to effectively manage it and ensure safe, reliable operation. When the various aging and degradation mechanisms are considered they can be classified into two general classes: (I) **Internal**: where changes are to microstructure or chemical composition that change intrinsic properties (e.g. thermal aging, creep, irradiation damage, etc.). **(II) Imposed**: where there is physical damage to the component, such as metal loss (corrosion, wear) or cracking or deformation (stress-corrosion, deformation, cracking). In practice there is more than just technology involved. There is a need for an effective management system which can correctly implement mitigation or monitoring actions [15].

In the management of degradation there are changes occurring in asset management methodologies, not least with enhanced state awareness and SHM that move beyond damage tolerance. It has been said that, "in many ways, materials damage prognosis is analogous to other damage tolerance approaches, *with the addition of in-situ local damage and global state awareness capability and much improved damage predictive models*" [16].

To implement "damage prognosis," new and different NDE approaches are needed for detection and characterization of materials degradation precursors. The nature of precursors depend on material type and the degradation mechanism. The mechanisms of interest in passive metallic components include fatigue (thermal and mechanical), SCC and embrittlement which all interact with local variations in residual stress, grain morphology and material chemistry, as well as local variations in elastic properties, electrical conductivity and magnetic permeability

4 NDE & Product development

NDE is increasingly being seen as a part of the engineering process, with companies seeking staff who can provide an analysis as a part of the design process. Such activities bring together the understanding of materials, manufacturing process and measurements, and in many cases now employ a multitude of models. This analysis can utilize process, failure, reliability, cost, stress and CAD models, all in the context of NDE and probability of detection analysis and these feed into life models. Such concepts are not new, but are seeing more use. There was a NIST funded program which sought to demonstrate a concurrent engineering approach, unified life-cycle engineering, in product development that included NDE as a full partner, as illustrated in Fig 7. These concepts are seeing further development and integration of NDE throughout component life cycle, including with both SHM – NDE and on into prognostics [17, 18].

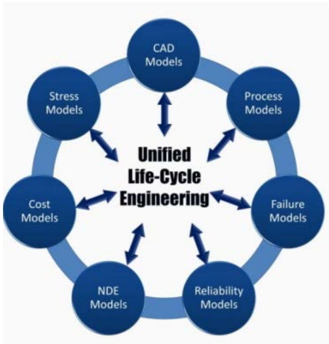

Fig 7. Schematic illustrating the concept of unified life-cycle engineering.

One driver for revisiting NDE approaches and ULCE concepts, which now go by several names, are the changes with advanced manufacturing. Such processes are seeing increased use of engineering composites and with new processes such as additive manufacturing, and growth in the use of powder metals. These changes in materials and processes are creating new challenges for measurement and sensors, including high temperatures and integration into manufacturing, and such needs are moving well beyond current NDE implementations.

The various approaches to advanced manufacturing are moving QA/QC metrology beyond dimensional characterization [19]. Techniques are needed to characterize texture, porosity, hardness as well as moduli, in real time. There is need for increased system integration, reducing measurement time and data processing. The advanced metrology also needs to be accurate, safe and at the same time provide measurement flexibility. Understanding of microstructure is a key ingredient in the development of state awareness strategies. An idealized scenario bridges between NDE and materials science, and brings together NDE measurements, the estimation microstructure parameters, macro material property estimation and an assessment of structural performance for engineering applications. In seeking to progress from NDE to performance, as seen in the lower part of Fig 4, there are generally, challenges at each link and these include (i) non-uniqueness, (ii) inadequate sensitivity of the measurement process to key parameters and (iii) limitations of the theory base. These challenges tend to force adoption of a stochastic approach. In particular when looking at determination of mechanical properties, this has remained a *holy grail* of NDT [20]. Some significant progress has been made, with for example ultrasonic stress measurement, but this area remains a topic for current research.

An example of ultrasonic methods that have been successfully employed for material characterization is ultrasonic backscatter for grain structure analysis. In rotating machinery, such as a Waspalloy disk, the scatter in material behavior is attributed to the inhomogeneous microstructure elements with metals. There is a need to be able to assess the initial state and then the progression of damage *before* cracks form. The quantification of initial state can be provided with ultrasound and the same approach used to check for the evolution of damage when possible and the validation of prognostic calls.

The process of backscatter characterization is described in a tutorial [21] and the process is illustrated with Figs 8-10 [12, 21]. Fig 8 shows a schematic for a pulse-echo measurement on a sample with defects and grain structure. A typical form for the resulting RF data is shown in Fig 8c. In many NDT measurements the gain is adjusted to minimize grain noise. However, it is these signals which provide information/characterization of the grain structural characteristics.

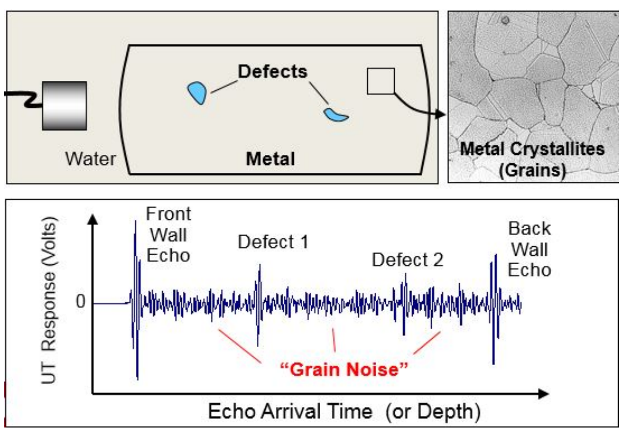

Fig. 8 Pulse-echo ultrasound (a) configuration, (b) microstructure of grains and (c) RF data.

The backscatter response is on a reference sample and a sample of interest. An example of a typical signal obtained from grain scattering is shown as

Fig 9. The data can then be analyzed to give attenuation as a function of frequency, which can be compared to scattering model data to give an estimate for grain size.

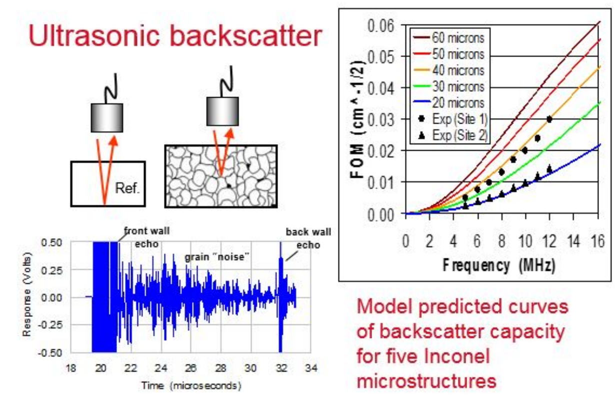

Fig 9 Pulse-echo reference and test sample, with example of RF data.

Results for predicted backscatter as a function of frequency for five Inconel microstructures, assuming a polycrystalline material with various grain sizes (20-60 micron) are shown in Fig 10. The sizing grain size estimated is obtained by comparing the model and experimental data. For the two experimental cases considered the "dots" align with a 40 micron material response and "triangles" correspond to a 20 micron material response.

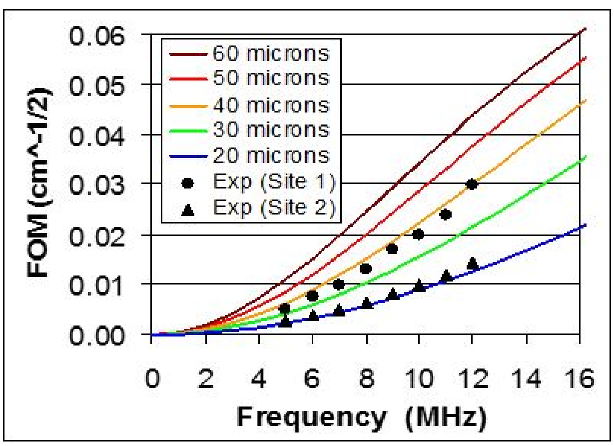

Fig 10 Model and experimental data for back scatter as a function of frequency.

5 Prognostics

There is growing interest in moving to be more proactive in condition assessment and towards providing an estimate for expected life, a prognostic. In this context a schematic showing in a conceptual form the process of bring together the various measurements and models is shown as Fig 11 [22].

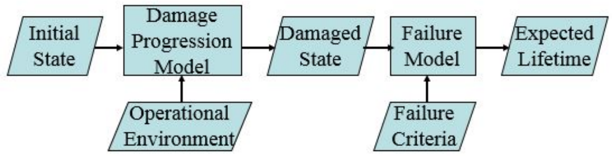

Fig 11 Schematic showing in a conceptual process for prediction of expected lifetime

In looking at this process (Fig 11) to go from an initial state to an expected lifetime would be a "done deal," IF the necessary input data were both correct and complete and models were of sufficient accuracy. They could be made computationally efficient and if there was sufficient computational accuracy. We don't have the data or the models, so quantification of what can be achieved is a current goal.

In terms of the barriers to being able to predict expected lifetime there is:

(i) **Missing information.** The methods used do not currently determine the initial state of individual components/structures/systems with high precision. In many systems there has not traditionally been adequate monitoring of the operating environment of individual components. Also damage progression models have traditionally been empirical (e.g., Paris Law), and it would be difficult to incorporate the missing information even if it were available.

(ii) **Uncertainty.** There will always be uncertainty in the input data

(iii) **Variability.** Even if it were possible to eliminate uncertainty, it would be necessary to take variability into account

In the context of aerospace applications addressing these challenges is being investigated. Monitoring of the operational environment is improving with new and improved temperature, strain and chemical sensors under development. For material state sensing data researcher attention is considering both global parameters, which include for structures strain, displacement, acceleration and in propulsion parameters such as vibration analysis. New and improved NDE tools are being developed, for example for local NDT measurements. There is interest in guided waves to sense structural changes; better ways to check for moisture and both ultrasonic and eddy current methods are being employed for sensing microstructure. Damage models are under refinement in many programs. Advanced NDE is seeking routine use of phased array technology, guided waves, diffuse fields and crack sizing using time-of-flight-diffraction (TOFD). For ultrasonic methods in SHM digital acoustic emission (AE) and Bragg Fiber Grating based AE sensing are all being considered for a diversity of applications, including energy systems [2, 6, 18].

It has been recognized that it should not be NDE or SHM, but that the two approaches are complementary and can contribute to giving data needed for advanced diagnostics and prognostics. NDE has been seeking more efficient inspections and expanding to full coverage of internal and hard to access structures. SHM seeks much broader coverage and demonstrated flaw sizing capability, but data are given in near real time, with an acceptable POD. The current SHM has limited coverage and flaw size detection capability, and has yet to demonstrate an acceptable POD, but data are given in near real time. It is the combination of NDE/SHM that seeks to accelerate progress to give the required coverage [23].

In looking to move beyond the simply approach presented in Fig 11, more comprehensive structures for diagnostics, prognostics and health management systems have been proposed and are shown in Fig 12 [24]. The state of development of advanced SHM application is advancing, but cost, weight and maintenance complexity are still barriers, at least some in some application, such as for wind turbines. Major progress has been made for monitoring rotating machinery, but structural component monitoring is still more at the research than the deployment phase [14].

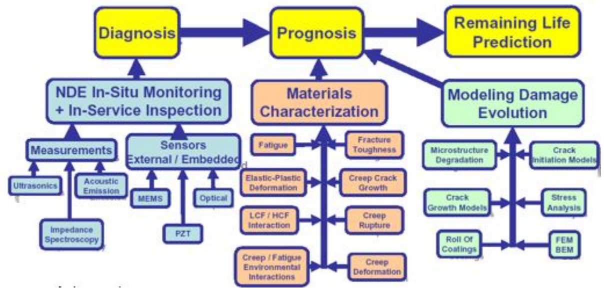

Fig 12. Schematic for a diagnostics, prognostics and health management system [24]

A final consideration is then the economic impact of NDT and SHM. Some analysis has been provided, including for applications to legacy nuclear power plants [25]. The progress and challenges in system health monitoring (SHM), for non-nuclear power system applications, was reviewed in a paper by Adams and Nataraju [26]. This paper includes the diagram given as Fig. 13, which provides a good visualization of the relationships between life, operation and economics.

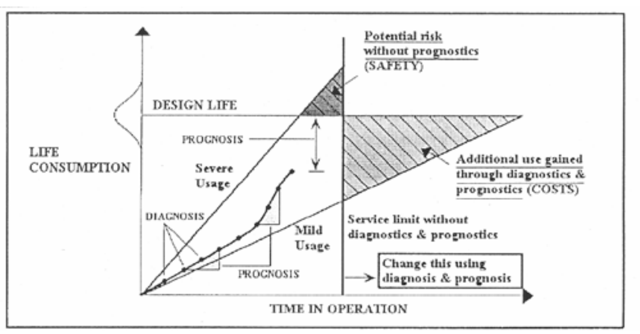

Fig 13 Overview of structural diagnostics and prognostics showing benefits in operation and support costs and safety [25]

6 Technical challenges

Conceptual frameworks and some theory have been demonstrated for well controlled cases in making material damage prognostic predictions. However applications are still limited and there are a number of technical challenges which remain. For sensing there are still issues with regard to what to measure and how to measure it. There are needs for better sensor materials which provide higher sensitivity to damage. When data are obtained there are now issues of “big data,” for example in pipeline, NDT there can be TByte data sets, which require interrogation, communication and integration. With the large data there can be issues not only with the sheer volume of data, but also data rates as a part is scanned or an in-service inspection tool moved through a pipe. In many cases detection of features of interest is hampered by achievable signal to noise ratio. For aging systems there can be challenges in extracting signals from noise in signals, to give early detection, and the sensors used in SHM can drift due to device aging. This further complicates ensuring stability of measurement systems/sensors over time.

As SHM and prognostics is considered there can be major challenges with regard to system integration and deployment on real-world hardware. Issues are complicated further as there is inadequate understanding of the phenomena of aging and degradation, particularly with regard to the effects of stressors. The available aging damage models are in many cases simplistic, and/or computationally intensive. In looking to predict life there is a need to adequately quantify and integrate data with process models.

The final series of challenges relate to the predictive/prognostic models, for symbiotic systems. There is growing interest in moving from a deterministic to a probabilistic analysis and risk informed in-service inspection (ISI) approach. For such insights to be useful there is the challenge of getting acceptance in moving beyond CBM to integration of prognostics into plant operation, specifically the O&M and cost-of-ownership associated with life cycle management. Finally an overarching challenge is the bounding and *quantification of uncertainty, when dealing with sparse data and in many cases ill-posed problems*.

A final question is then: does advanced NDE, looking towards diagnostics and prognostics have an impact? One example is the activities under the Engine Titanium Consortium [27]. The goal was to provide reliable and cost-effective tools for detecting cracks, inclusions, and imperfections in critical rotating materials and hardware. It was an ISU-led consortia with GE Aviation, Pratt & Whitney, Rolls Royce and Honeywell, where CNDE provided fundamental understanding in support of engineering applications expertise at the OEMs. This activity resulted in numerous changes to inspection practice throughout the life-cycle of jet engines. It is credited with resulting in a factor of five reduction in number of catastrophic engine events.

7 The Future and conclusions

Traditional NDT is a robust family of technologies and a solid foundation in measurement science. NDT and its more quantitative form NDE are seeking applications growth. The introduction of new materials and processes, together with the challenges of application to legacy infrastructure are making the R&D problems harder.

NDT/NDE are increasingly seen as a part of CBM/Prognostics and the total quality approach in the manufacturing process. In looking for systems in service, NDT is being used to minimize ownership costs. In so doing there remain needs for NDE to be more quantitative and more sensitive, particularly with regard to giving data for material state and early damage/degradation detection. There are needs to develop tools for early damage characterization. It is no longer adequate to just screen for macro-defects.

There is increasing use of robots. There are growing challenges faced in the processing of large data sets. There are needs for new sensors, and the integration of “NDE” into manufacturing metrology. As inspection becomes part of component management throughout its life cycle, there is a trend to move from SHM to true prognostics, at system level. There is growing adoption of approaches that employ the concepts in unified life cycle engineering (ULCE) with the full integration of NDE into engineering and product life cycle – design for inspectability and monitoring.

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