Power, Petrochemical/ Refining and Process Plant

Survey of Advanced Inspection Techniques & Recommendations for Best Practices

(*Acronym*: **Adv. Inspection Techniques**)

Final Report

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Executive Summary

Regular and reliable inspections are an integral part of any effective industrial plant maintenance programme. The success of such a programme relies, to a large extent, on the ***Non-Destructive Examination*** (**NDE**) techniques used. Hence, it is important for the user to understand the scope and limitations of the NDE tools that are available in order to maximise the effectiveness of each of the scheduled inspection activities. Furthermore, in today's competitive environment plant operators need to reduce maintenance costs by minimising downtime. Lower downtimes and greater reliability and accuracy can both be achieved by using some of the newly developed, more advanced NDE techniques. In addition, new higher performance higher efficiency plant may use newly developed materials which may require the use of new more advanced NDE techniques to quantify damage and assess component integrity.

This report provides a *state-of-the-art review* of recent advances in inspection techniques, including new and emerging NDE methods, and a critical evaluation of their effectiveness and success in practice. The information has been obtained from the plant experience of ETD experts and consultants, personal contacts in the industry worldwide, feedback from some of the industrial sponsors, in-house reports, published literature, and information available from manufacturers and users of inspection equipment.

The inspection technologies reviewed are those used to detect and quantify a wide range of damage types, including creep, fatigue, corrosion, etc. Emphasis is placed on the potential value that the inspection techniques would bring to the user by highlighting:

- The speed, reliability and accuracy of the technique in detecting and quantifying the damage *at an early stage.*
- The scope (material, geometry, environment, etc) and extent of the area coverage of the inspection technique.
- The flexibility of the inspection tools, including automated or robotic-based systems that enable remote and rapid inspection of confined/ non-accessible spaces.
- The level of automation of data recording and their interpretation/ presentation (e.g. displayed in image form) for fast and effective decision-making.
- The requirements of the NDE activities in terms of component preparation and/or disassembly; delays while components cool down to temperatures suitable for human inspectors and equipment; level of expertise required; calibration; etc.

The information and recommendations in this report are aimed at the plant operators to provide an overview of the recent advances in NDE and emerging inspection techniques. However, the report should be equally useful to service providers and plant designers who need to be aware of the new developments. The report contains large individual sections dealing with the different inspection techniques, including enhanced visual inspection methods, eddy current testing, radiographic examination, ultrasonic testing, etc. Recommendations are provided on the application of the inspection techniques in the industrial sectors represented by the project sponsors which cover a wide range such as power, petrochemical, refining and aerospace

sectors. The transfer of NDE techniques used successfully in some industrial sectors (e.g. aerospace and defence) can be of great benefit to others (such as power generation, petrochemical and refining).

The report starts by addressing ***enhanced visual inspection*** methods. Details are given of two visual inspection techniques that have emerged in recent years: *Dual-pass light reflection* (D-Sight) and *Edge of Light* (EOL). Surface and near-surface flaws, such as corrosion in metals and impact damage in composites, cause local surface deformation. Both of the new inspection techniques enhance the appearance of the surface deformation and increase its visibility. In addition to these image enhancement techniques, the report provides details of penetrant testing above 50°C, which reduces testing times compared to room temperature testing, as well as being intended for on-site examination of hot component surfaces.

A number of techniques have emerged in the field of ***eddy current*** testing. In order to simplify the detection of flaws, the Magneto-Optics Imager (MOI) was developed as a means of visualizing the eddy current response. Flaw depth information can be obtained with the pulsed eddy current (PEC) method. The method called SQUID can detect cracks in thick or multi-layered metallic structures, and it has been shown to be superior to conventional eddy current systems.

In recent years, there have been a number of developments in the field of ***radiographic examination***. In particular, *real-time* imaging for radiographic visualisation has helped overcome the time-consuming process that was involved with film recording, and computer processing of *digitised images* has enabled the enhancement of the images, as well as the quantification of the inspection criteria. Furthermore, while X-ray sources used to have very large high power units and were therefore restricted to fixed installations, recent developments have resulted in *semi-portable* X-ray units that are now being used for at-site inspections. As well as these developments, a number of advanced radiographic techniques are considered in the report, including computed tomography (CT) scans, reverse geometry X-ray (RGX) and microfocus X-ray microscopy.

Ultrasonic testing encompasses a versatile range of NDE methods. A number of recently developed and newly emerging techniques are discussed in the report. Techniques have been developed employing the various wave modes as well as scattering and mode-conversion that are associated with the wave interaction. Dry coupling methods have been introduced, including air-coupled piezoelectric transducers, Electro-Magnetic Transducers (EMAT) and laser ultrasonics, while probe and couplant technologies are being developed for high temperature, on-line application of UT.

Two powerful ultrasonic techniques have emerged in recent years: ***Time-of-flight diffraction (ToFD)*** and ***Phased Arrays.*** These techniques offer improved accuracy in locating and sizing cracks, improved capability to detect crack development in its early stages, and much faster inspection rates than radiography or conventional ultrasonics. ToFD differs from conventional pulse-echo ultrasonics in that it depends on diffracted energy rather than reflected energy. An ultrasonic array is a single transducer that contains a number of individually connected elements. Each element in the array can be pulsed in sequence, and with the appropriate phasing delays to allow a range of beam angles to be produced. Thus, the beam can be swept through an angular range allowing optimum beam angles to be used for the inspection. Recent years have seen a dramatic increase in the use of ultrasonic arrays for NDE. This is because arrays offer great potential to increase the inspection quality and reduce the time required to perform the inspection. *Focused Annular-Array* UT probes allow the ultrasonic energy to be concentrated in a small region of the testpiece, which results in high sensitivity. This technique has the capability to detect *incipient creep damage*. The *ultrasonic backscattering* technique also has potential for monitoring the development of creep cavitation damage. These advanced ultrasonic techniques are discussed in detail in the report, together with examples of their applications.

Long-range guided wave UT inspection is still an emerging technology but is already used for the inspection of pipelines and piping in refineries and chemical plant. The technique can provide 100% volumetric inspection.

Traditionally, the monitoring of the damage/cracking in high temperature plant was done off-line through periodic inspections, however with the increase of the equipment age, the frequency of the inspection can become significantly higher, resulting in excessive maintenance costs. A less costly long-term solution is the use of *on-line* crack monitoring techniques, such as ***Acoustic emission*** (AE) and the ***electrical potential drop*** method, which are discussed in this report. AE has been widely used in various industries for on-line detection and monitoring of cracking. *Quantitative Acoustic Emission* (QAE) is a recent development of AE that can be used for periodic monitoring and as a pre-outage screening tool with 100% component coverage, which will reliably pinpoint defect locations and areas of concern. Recently, the electrical potential drop method has been applied to crack monitoring on plant components, and the ACPD technique has shown potential for monitoring creep cavitation damage. The principles and applications of AE and ACPD methods are described in this report.

An alternative inspection method that has been applied to the detection of surface-breaking cracks is the ***Alternating Current Field Measurement*** (ACFM) technique. This is a non-contacting electromagnetic technique that can be used to inspect through non-conducting coatings, and probes are available for elevated temperature applications.

Measurement of strain may be performed for the purpose of assessing the magnitude of the deformation itself or for determining the stress acting on a component. ***Capacitance strain gauges*** are effective for on-line monitoring of creep deformation in high temperature components, such as main steam pipes and bends, where the life fraction consumed is high. Alternative techniques based on speckle image correlation methods have been developed for monitoring localised straining in weld heat-affected zones. Capacitance strain gauges and the ***SPICA*** technique, which has been used for on-line strain measurements in power plant, are described in the report.

X-ray diffraction (XRD) is a well-known laboratory technique that reveals detailed information about the chemical composition and crystallographic structure of a material. XRD is difficult to apply in the field. However, in recent years, some equipment manufacturers have started to develop ***portable XRD*** (XRPD) instruments, which will enable inspection directly on-site. A prototype version is illustrated in the report.

Compared with laboratory measurements using stationary hardness testing machines, on-site hardness measurements made using portable testers show a large amount of scatter and there is considerable uncertainty in the accuracy of the measurements. A laser-guided ***portable hardness testing*** equipment has been developed recently in Japan. This equipment significantly improves the accuracy of on-site hardness measurements. It is now being used by ETD to evaluate the remaining life of P91 piping welds in power plant.

The rate of corrosion dictates how long any plant component can be usefully and safely operated. However, corrosion rarely takes place at a steady rate for prolonged periods, and usually there are some short periods of very aggressive attack and relatively long periods of little or no attack. The periods of high corrosion rate often go unnoticed until significant damage or failure has occurred. Subsequent analysis of the damaged/failed component may not be able to confirm what was the root cause and when it happened, whereas on-line monitoring of corrosion rate can provide the answers. This report discusses the application of the ***corrosion scanner systems*** that can provide on-line corrosion mapping of boiler furnace walls.

Thermal infrared testing is used to measure or indicate the temperature distribution at the surface of the object at the time of test, for the purpose of identifying the presence of a discontinuity or loss of wall thickness. Leakages in plant components or areas of overheating can easily be detected using ***infrared thermal imaging*** systems. This report considers some applications of thermal imagers in petrochemical and power plant.

Digital ***shearography*** senses out-of-plane surface displacements in response to an applied load. The capability of shearography to inspect large areas in real time has significant advantages for many industrial applications, including inspection of composite structures and pressure vessels.

A section of the report considers the ***flaw sizing capabilities*** of various NDE techniques. This provides a comparative insight into the NDE techniques capable to provide complete and accurate sizing of flaws in industrial components. This section includes a detailed examination of crack sizing using UT (including ToFD) and advanced eddy current methods. The report also includes a section in which the ability of various NDE techniques to measure the ***corrosion metrics*** is considered.

Atomic or Scanning Force Microscopy (SFM) has in the past been used for the study of organics and clinical materials. However, recently its use for the study of metals and alloys used in industry has been investigated with a great degree of success. ETD are at present studying the use of SFM for the early stage creep cavity damage detection in P91 components (used in high temperature plant) with a great degree of success. The company is now trying to develop a portable version of SFM for the in-plant use.

One advantage of SFM is that not only it gives a high degree of resolution (better than most Scanning Electron Microscopes - SEM) for, say, creep cavity resolution, it can also measure the volume of cavities thus giving a better measure of a three dimensional damage. Indeed it is hoped that this development in the near future will render the making of replicas for assessing in-service creep damage a thing of the past, thus saving a great deal of money and time.

The report also includes a section looking at some ***examples of the NDE technologies*** that are being used in various industries. Examples include application of NDE in the life management of *steam turbine rotors*, defect characterisation and flaw sizing in *nuclear power plants*, and the advanced NDE systems for inspection of *gas turbine* components. NDE methods for inspecting ceramic *Thermal Barrier Coatings* are also discussed in the report.

The concluding section of the report provides a summary of the main findings of the review and the recommendations for best practices.

CONTENTS

1. INTRODUCTION

Regular and reliable inspections are an integral part of any effective industrial plant maintenance programme. The success of such a programme relies, to a large extent, on the ***Non-Destructive Examination*** (**NDE**) techniques used. Hence, it is important for the user to understand the scope and limitations of many of the NDE tools that are available in order to maximise the effectiveness of each of the scheduled inspection activities. Furthermore, in today's competitive environment plant operators need to reduce maintenance costs by minimising downtime. Thus, for example, new ultrasonic sensor heads are being developed which will be able to operate much above room temperature. This can help with the inspection of high temperature plant without waiting for them to cool down to room temperature and can therefore result in large savings in terms of lost production. Both lower downtimes and greater reliability and accuracy can also be achieved by using some of the newly developed more advanced NDE techniques.

For implementation of NDE it is important to describe what shall be found and what to reject. For this reason testing specifications are indispensable. Nowadays there exists a great number of standards and acceptance regulations. They describe the limit between acceptable and non-acceptable conditions, but also often which specific NDE method has to be used.

The reliability of an NDE method is an essential issue. But a comparison of methods is only significant if it is referring to the same task. Each NDE method has its own set of advantages and disadvantages and, therefore, some are better suited than others for a particular application. By using artificial flaws, the threshold of the sensitivity of a testing system has to be determined. If the sensitivity is too low, defective test objects are not always recognized. If the sensitivity is too high, parts with smaller flaws are rejected which would have been of no consequence to the serviceability of the component. With statistical methods it is possible to look closer into the field of uncertainty. Also the aspect of human errors has to be taken into account when determining the overall reliability.

Personnel qualification is an important aspect of non-destructive evaluation. NDE techniques rely heavily on human skill and knowledge for the correct assessment and interpretation of test results. Proper and adequate training and certification of NDE personnel is therefore a must to ensure that the capabilities of the techniques are fully exploited.

NDE is now a relatively mature field, even though accurate characterization of hidden flaws may still pose a challenge. The majority of the current NDE methods were introduced around the middle of the twentieth century. Modifications, improvements and enhancements have contributed to an unprecedented advancement in capability and reliability of these methods and the emergence of new ones. As an interdisciplinary field, NDE benefited from capabilities that were developed in many other science and engineering fields. The resulting improvement has touched every element of the NDE technology, leading to smarter, smaller, lighter and significantly more capable instruments. The requirements for NDE are continuing to be driven by the need for lower cost methods and instruments with greater reliability, sensitivity, user friendliness and high operational speed.

Traditional ultrasonic inspection techniques, although proven effective in detecting subsurface cracking, are still only a means of defining internal damage prior to failure and are less effective in defining damage accumulation/extent. Hence, a conservative approach is generally adopted in such situations, resulting sometimes in unnecessary corrective actions and associated costs. In contrast, *emerging technologies* such as the *'ultrasonic phased arrays'* provide the means to quantify damage more precisely and perform repairs only when necessary. In addition, in some materials and components detection of damage by using more advanced and accurate NDE techniques can help identify a problem at an early stage, thus enabling the plant owner/ operator to take corrective measures before the component cracking/ failure takes place.

The transfer of NDE techniques successfully used in some industrial sectors (e.g. aerospace and defence) to others (such as power generation, gas, refining) can be of great benefit. Indeed the newly developed tools such as the *'long-range guided-wave'* technique, now widely used in the oil industry for piping inspection, is already finding its application in the power industry for inspecting boiler equipment. It is being particularly used in the inspection of boiler tubes as it can provide comprehensive information on the tube condition without requiring extensive preparation and long inspection time.

There are also developments in '*IRIS inspection techniques'* that have traditionally been used for condenser tube inspection and are now being applied to water tubes in boilers and HRSGs with some success. EMATS of furnace wall tubes has been used extensively and successfully in many stations for a number of years saving significant downtime on plants. These are some of the techniques and developments which are reviewed and evaluated in this project.

This report aims to assess the performance and results of the plant inspection techniques through a wide ranging and critical review of the existing NDE techniques including many of the *advanced tools* developed recently. New technologies used in *other industrial sectors* (aerospace, refineries, chemical plant, defence etc.) and their potential application in the industrial sectors of interest to the sponsors of this project are also assessed. The emphasis is on technologies that have the capability to improve the accuracy of damage detection and more specifically quantification, to increase the scope/ coverage of the inspection (a larger area of the surface and greater depth) and reduce the component surface preparation work, thus reducing significantly the maintenance and outage costs.

The **objectives** are to review the state of the art of both existing and emerging NDE techniques and provide a critical and independent evaluation of their effectiveness and success in practice. Various stakeholders such as technology developers, service providers, plant operators and R&D performers, some involved with ETD in collaborative projects, have been contacted and/or interviewed in order to review the knowledgebase and accumulated experience. Recommendations are provided on NDE applications in the industrial sectors represented by the project sponsors.

The inspection technologies reviewed are those used to detect and quantify a wide range of damage types including, but not limited to:

- Corrosion (general, steam side corrosion, gas side corrosion, flow assisted corrosion, oxidation, stress etc.).
- Creep cavitations and/or cracking.
- Fatigue damage, including creep-fatigue, thermal fatigue and corrosion fatigue.
- Material degradation (ageing, temper/hydrogen embrittlement, etc.).

The international industry experience with the use of inspection techniques is reviewed with emphasis on the potential value that it would bring to the user by highlighting:

- The speed, reliability and accuracy of the technique in detecting and quantifying the damage *at an early stage*.

- The scope (material, geometry, environment, etc.) and extent of the area coverage of the inspection technique, including detection of defect/damage within the wall thickness.
- The flexibility of the inspection tools, including automated or robotic-based systems that enable remote and rapid inspection of confined/ non-accessible spaces.
- The level of automation of data recording and their interpretation/ presentation (e.g. displayed in image form) for fast and effective decision-making.
- The requirements of the NDE activities in terms of supporting efforts such as:
    - Component preparation and/or component disassembly.
    - Scaffolding, or delays while components cool down to temperatures suitable for human inspectors and equipment.
    - Calibration.
    - Level of expertise.

This report reviews up-to-date knowledge base and industry and research experience with a proper introduction to the techniques reviewed. It should therefore be of much value as a reference base to the new and experienced engineers alike who are involved in the use of NDE techniques or who need to know the usefulness of these techniques for plant integrity and life assessment of industrial structures.