Official Journal of the British Institute of Non-Destructive Testing

INSIGHT

Vol 64 | No 11
November 2022

Non-Destructive Testing and Condition Monitoring

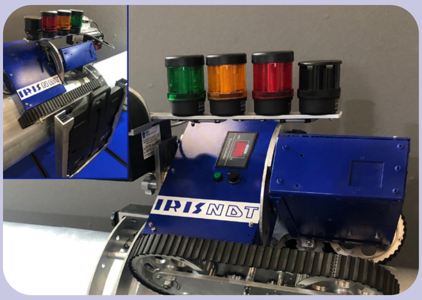
Official Journal of the British Institute of Non-Destructive Testing

INSIGHT

Non-Destructive Testing and Condition Monitoring

Volume 64 Number 11 November 2022

This month's cover



Although corrosion under insulation (CUI) is not a new damage mechanism in the process industries, affecting both the insulated plant and pipe, IRISNDT is regularly challenged by its clients to deliver screening techniques that have the potential to reduce the cost of removing and reinstalling large sections of insulation unnecessarily.

IRISNDT has a substantial suite of procedures and software applications for inspecting for CUI, which have traditionally followed the guidelines available from the HSE for detection methods[1], such as pulsed eddy current, guided wave ultrasonics, flash radiography, real-time radiography and thermography (when conditions suit).

The company's most recent development is its investment in the Teledyne CP Battery CP120B, a battery-operated portable X-ray generator, and the Teledyne Go-Scan 4335, a portable digital radiography detector, which will work in conjunction with IRISNDT software and tablet devices to enable a direct visual display of the image produced.

To enhance this system further, IRISNDT has designed and developed its own semi-automatic system to deploy the equipment, which ensures its employees can maintain safe distances while producing real-time images.

This month's front cover shows the IRISNDT Optic with its bespoke central bearing, to enable mounting on different diameters and surfaces efficiently.

IRISNDT has offices in the UK, the USA, Canada and Australia, all providing a wide variety of NDT and inspection services.

IRISNDT
www.irisndt.com

[1]SPC/Tech/Gen/18, HSE Operational Guidance.

Published by:
The British Institute of Non-Destructive Testing
Midsummer House, Riverside Way, Bedford Road
Northampton NN1 5NX, UK
Tel: +44 (0)1604 438300 | Fax: +44 (0)1604 438301
Email: info@bindt.org | Web: www.bindt.org

Features

NDE RESEARCH

GUIDED WAVES

ULTRASONIC PULSE VELOCITY

INDUSTRIAL CT

Regular Features

DOI: 10.1784/insi.2022.64.11.625

The RCNDE industrial members' 2022 vision for the future requirements of NDE

C R Brett and P Thayer

The UK Research Centre in Non-Destructive Evaluation (RCNDE), established in 2003, has become a leading industrial-academic collaboration for undertaking industrially relevant research in the fields of non-destructive evaluation (NDE) and structural health monitoring (SHM). The industrial members produced their first five-, ten- and 20-year vision for NDE in 2011 and updated it in 2016. This article describes the newly updated vision for NDE that was produced by the industrial members in 2021/2022. The overall vision presented in this article is a consolidation of the individual industrial sector visions, a process that is possible due to the fact that many longer-term objectives are common across sectors. This enables research projects to be defined that appeal to multiple industries and demonstrates the power of collaboration to deliver relevant solutions. To aid understanding, the responses have been grouped into three themes: improvements desired in the capabilities of NDE technologies; asset-based inspection challenges that need to be met; and aspects that deliver and help to realise the benefits of Industry 4.0. The vision produced by RCNDE's industrial members will be used to shape the core research programmes and identify opportunities for new collaborations. It will help to bring forward the application of inspection and monitoring technologies to meet future industrial needs and timescales.

1. Introduction

1.1 Background

The UK Research Centre in Non-Destructive Evaluation (RCNDE) was founded in 2003 and is an industrial-academic collaboration devoted to furthering non-destructive evaluation (NDE) research internationally and building the UK's NDE skills base. It is given direction by its industrial membership and is managed by NDE Research Association Ltd (NDEvR), a not-for-profit company that collectively represents the industrial members.

The industrial membership has grown from five at the start to about 60 today. This includes 14 Full Members, who have a seat on the Management Board and are able to propose, guide and review all of the projects that are undertaken. The membership covers aerospace, power generation (nuclear, conventional and renewable), nuclear reprocessing and waste management, defence, oil & gas, manufacturing, transport and the public sectors. Several members are active in multiple sectors and most operate internationally (see Table 1). There are also about 45 Associate Members who represent the NDE supply chain, either by providing services to end-users, manufacturing or supplying equipment, sensors and software or representing other formations of engineering companies. Some Associate Members are spin-out companies from previous RCNDE research programmes.

RCNDE research projects are undertaken by eight UK universities (an increase from the original six): Bristol, Imperial College London, Liverpool, Manchester, Nottingham, Southampton, Strathclyde and Warwick. In addition, an associated Centre for Doctoral Training called Future Innovation in NDE (FIND) manages the cohorts of EngD and PhD students who are active in many projects. Since 2005, over a hundred students have completed their doctoral degree and many have moved on to NDE careers in academia or industry.

RCNDE was formed to provide direction, leadership, synergy and structure to the way that research in NDE is performed. Note that the use of the term NDE should be understood to include non-destructive testing (NDT) and the allied fields of condition monitoring (CM) and structural health monitoring (SHM). Prior to RCNDE, each of the industrial members had their own inspection challenges that were usually addressed through in-house development programmes or collaborations with a set of companies that shared their needs. This was often to satisfy short-term operational requirements with limited proactivity shown to address emerging opportunities, longer-term requirements and threats. Efforts were probably duplicated in different companies or sectors, key development opportunities might have been missed if funding was insufficient and the role of industrial NDE staff was often limited to watching the supply chain for relevant developments that could be adapted to their own needs. This approach tended to be reactive and could lead to piecemeal solutions. The role of RCNDE has been to provide a powerful and effective framework that overcomes many of these problems for its members, with far-reaching benefits for the global industry. Industrial companies can come together to provide guidance to the researchers that not only covers their immediate inspection requirements but outlines their strategic needs as they adapt to the changing regulatory, market, safety and environmental drivers that affect their businesses. Academia benefits from receiving detailed information about industry's priorities and plans for the future and can therefore formulate proposals that are relevant, timely and useful, while industry benefits from sharing experiences with other companies and, importantly, pooling their funds to gain a synergistic advantage that could not be reached individually.

● *Submitted 11.08.22 / Accepted 28.09.22*

Colin R Brett is the Technology Director of RCNDE. Email: colin.brett@ndevr.org.uk

Peter Thayer is the Industry Director of RCNDE and a Director of NDE Research Association Ltd (NDEvR), a not-for-profit company representing the collective interests of the industrial members of RCNDE. Email: peter.thayer@ndevr.org.uk

Table 1. Full industrial members and the sectors in which they are active

	Company													
Sector	Airbus	Rolls-Royce	BAE Systems	DSTL	IHI	EDF	NDA	Jacobs	Hitachi	ONR	Shell	BP	Petrobras	Tenaris
Aerospace	x	x	x	x	x									
Power					x	x	x				x	x		
Nuclear		x			x	x	x	x	x	x				
Defence	x	x	x	x										
Oil & gas								x			x	x	x	x
Manufacturing	x	x	x		x				x					x
Transport	x	x							x					
Public sector				x						x				

1.2 RCNDE research programmes

It is striking that many industrial sectors share common objectives, especially at the lower technology readiness levels (TRLs) 1-3, where the fundamental research is performed‡. For example, the improved inspection of welds, either during manufacture or in service, is common to most of the industrial members. Therefore, despite materials and locations/environments often varying between sectors, there is a huge benefit in being able to combine resources to tackle fundamental problems such as this. RCNDE's 'core' research programme contains projects that are relevant to most, if not all, of the industrial members, while for more specific problems that might be limited to just one industrial sector, RCNDE also performs 'targeted' research projects. Some smaller 'feasibility' projects are also conducted to perform an initial investigation of promising avenues of research, as well as 'technology transfer' projects, which aim to facilitate the movement of innovations into the field and their further exploitation.

The full suite of projects is reviewed on a regular basis by the RCNDE management team and the full industrial members to ensure that they remain relevant and are performing to plan. An International Advisory Board of independent NDE experts regularly assesses the research projects and stays engaged with them to ensure a constantly high quality of research while maintaining focus on the industrial needs.

1.3 Impact of RCNDE research

A recent internal review of all of the RCNDE projects that have been undertaken since 2003 (see Figure 1) has shown the following: 48% have been implemented in some form by the industrial members, either by creating a spin-out company to sell a service or product or to solve a specific company inspection requirement; 23% have been paused, either because the inspection challenge lowered in priority or the particular technology being investigated was not sufficiently capable at that time; 6% were terminated because the inspection requirement was no longer needed or the technology was proven to be insufficiently capable; and 23% are ongoing projects that have not yet reached a conclusion. This represents a healthy set of

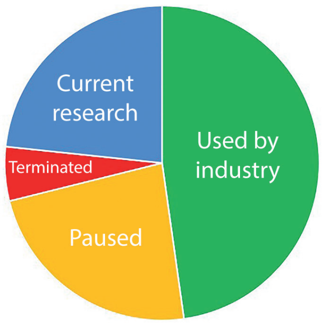


Figure 1. RCNDE project outcomes 2003-2022

outcomes that is delivering far more for RCNDE's membership and beyond than has traditionally been achieved.

Three phases of RCNDE have been completed to date and the fourth is underway, so it is possible to measure the progress of projects through the TRL scale over time. During 2020-2021, every project within each completed phase was reviewed and its current TRL was determined, resulting in an average TRL for each phase, as shown in Table 2.

Table 2. Average current TRL of projects within each phase of RCNDE

Phase	Dates	Number of projects	Average TRL
RCNDE1	2003-2008	29	5.6
RCNDE2	2008-2014	31	4.3
RCNDE3	2014-2020	30	2.7

Collectively, there is a progression of about 1.5 TRLs per phase of RCNDE. Of course, some individual projects will progress more quickly and others more slowly.

Figure 2 presents the number of projects at each TRL, with separate curves for each phase of RCNDE. Note that non-integral values arise because some technologies straddle two or more TRLs, so their 'scores' are spread proportionally. The oldest projects from RCNDE1 have mainly (but not entirely) moved away from academic research at TRL 1-3 and can be found at TRL 4-7, with a significant number having become fully commercialised at TRL 9. The most recently completed phase of RCNDE, RCNDE3, has most projects at TRL 1-3 with no projects above TRL 6. It is these projects that will benefit from technology transfer funding to facilitate field trials. Projects from RCNDE2 lie between the two curves with the majority of projects at TRL 3-4, but with a small number already

‡Technology readiness levels are a standard means of assessing the stage of development and innovation of novel ideas and techniques. TRL 1 represents the most basic understanding of new principles and ideas, while TRL 9 represents the routine use of any idea or technique in industry. TRL 1-3 is typically the realm of university research and TRL 7-9 is the commercialisation of new products and processes. TRL 4-6 is recognised as the main gap to bridge and necessary for successful innovation.

feeding through to commercialisation at TRL 9. The overall data shows a good progression of technology readiness with time and it is planned to continue and accelerate this trend with continued direction from industry via the vision set out in this article.

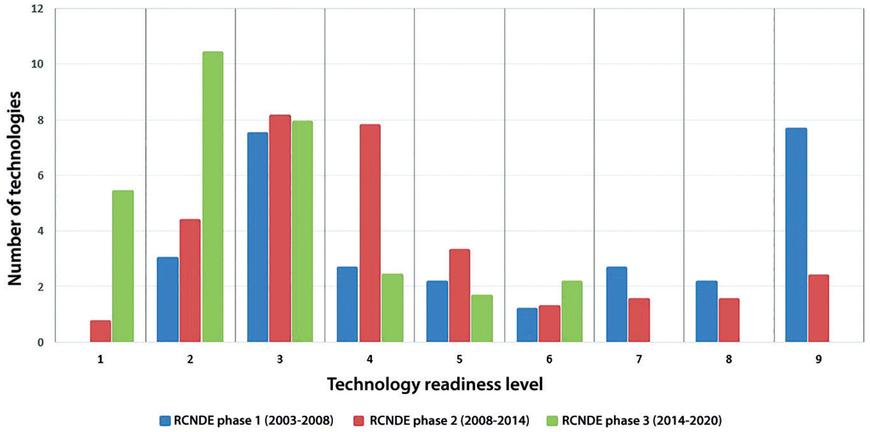


Figure 2. Progression of current TRL for the completed phases of RCNDE

2. Building the 5-10-20-year vision for NDE

The term '5-10-20-year vision' refers to the desired technologies, products and services that will be needed in five, ten and 20 years' time, assuming similar rates of development to those that have been achieved in the past. They can be considered to be near-, medium- and long-term horizons.

2.1 History of the vision

The fact that RCNDE has produced many technologies that have found uses within industry is not down to pure chance. From the outset, the industrial members have provided direction and target capabilities for implementation and this was formalised into the first 5-10-20-year vision that was produced in 2011[1]. It took into account the individual business trends in the various industrial sectors, emerging innovations, technological trends and a broad range of drivers, including regulatory, market, safety, environmental and economic factors. This vision allowed the academic members to obtain a clear understanding of the industrial requirements and priorities and to produce research proposals that aligned with those needs.

This vision was refreshed five years later in 2016[2] to produce updated objectives, retiring those that were no longer relevant or had been achieved and introducing new ones where necessary. The 2016 vision provided the target themes for an open call for project proposals from any UK university in March 2019. The successful projects have become the current core research programme and the successful universities formed the academic membership for the fourth phase of RCNDE: referred to as RCNDE4. The second vision update, described here, was undertaken after another five years, in 2021/2022, and is expected to remain valid until 2026.

2.2 Structure of the vision

To build the five-year vision, a good starting point is to consider technologies that are emerging today and think about their state of development five years ago. This gives a sense of the typical speed of development and so, as becomes apparent, if a capability is to be implemented in five years' time and produce a benefit within industry, then development in that capability must be underway already. Technologies that are already at TRL 3 are those that could, over a five-year period, be progressed to TRL 6 (prototype demonstrated in a relevant environment), TRL 7 (demonstrated in an operational environment) or higher. Many of the projects that are undertaken by RCNDE fulfil this category as it is often the shorter-term business needs of the industrial members that drive the scope of the project portfolio. Therefore, the technologies that will be needed in five years are most probably those under development by RCNDE and similar organisations today.

The ten-year vision addresses the expected business needs of the industrial members in ten years' time, taking into account industry trends in their own sectors and broader societal issues such as the requirement to protect the environment. The consultation process allows the industrial members to step beyond their immediate needs for NDE and be more speculative in how technologies could be developed, adapted and combined to satisfy a goal. To achieve this aim over a ten-year period, there must already be some level of knowledge and understanding to justify the candidate technologies and a path for development should be broadly apparent. Candidate technologies are likely to be those that are already at TRL 1 (basic principles observed) or TRL 2 (concept and/or application formulated).

The 20-year vision is an opportunity to be more speculative and explore new ideas for beneficial future capability without necessarily binding them to current knowledge and capability, while recognising that there must be a connection to the objectives that can be foreseen today.

The industrial members were asked to reflect on what they would like to be able to do if only the technologies were available to allow it and also consider those inspections and measurements that they currently 'cannot do' because NDE methods and delivery mechanisms do not exist. It assumes that there will be no limitations imposed by the supporting technologies, such as computer processing speeds, data storage capacities, performance of materials, availability of funding, etc, *ie* all the perceived external constraints will have been satisfied. Note that the term '20-year' is a generic term for the long-term horizon, so some ideas might not come to fruition until beyond 20 years.

It is important to include quantitative targets for the desired future capabilities in the vision, where this is possible, so that researchers fully understand the challenges involved. For example, the term 'better coverage' is to be avoided and replaced by a measure of area inspectable per hour or day, or a specified factor to represent the improvement on present day capabilities.

2.3 Methodology and participants

Individual 5-10-20-year vision documents were produced for the various industrial sectors and these were then combined into a single, overall 5-10-20-year vision that allowed the whole picture to be assimilated. This is possible because the longer-term aims for NDE in all sectors are often similar, it is only in the shorter term that differences due to materials, damage mechanisms, operating environment and business constraints tend to resolve themselves into sector-specific objectives. The RCNDE members have access to the full details of the individual visions; it is a summary of the overall 5-10-20-year vision that is presented in this article.

The updated vision was produced using information provided by a wide range of organisations, but primarily by the full industrial members who are responsible for steering the overall research portfolio. They participated in sector-based meetings, initially to review progress against the previous (2016) vision, to highlight objectives that had been fully or partially achieved and to identify any previous objectives that were no longer relevant to their requirements. This was followed up by separate sector meetings to define the forward view and set targets for performance, etc.

A separate meeting was held with Uniper and RWE to supplement the information on the conventional (non-nuclear) power generation and renewable sectors. This was further reinforced by information that was gained earlier during a Workshop on NDT and SHM Requirements for Wind Turbines, organised by BINDT and RCNDE, which was held at the Offshore Renewable Energy Catapult, National Renewable Energy Centre, Blyth, UK, in February 2019[3].

RCNDE's Associate Members, who mainly belong to the supply chain, offering equipment and/or services to industry, were also invited to contribute on where they envisaged shortfalls in research capabilities and the direction of future trends.

Links have also been made with the Aerospace Technology Institute (ATI), which is an independent not-for-profit organisation that has a role supporting the UK government's Department for Business, Energy and Industrial Strategy (BEIS)[4]. It was agreed that there would be advantages in sharing the updated RCNDE aerospace vision and the ATI 'Roadmap for NDE', since the ATI provides advice to Innovate UK and this might lead to future technology transfer funding relevant to aerospace NDE.

While manufacturing is common to all of the industrial sectors represented it is not the primary focus for many of the members, so a further meeting was held with the National Manufacturing Institute Scotland (NMIS)[5] in April 2022 to establish their views on the future requirements for NDE.

Finally, a meeting was held in September 2021 between members of the FIND Doctoral Training Centre[6] and potential industrial sponsors to discuss ideas for future projects.

Due to the disruption caused by the COVID-19 pandemic in 2020-2021, all of the meetings apart from the Renewable Energy Workshop were held virtually. It is interesting to note that five years ago only a minority of organisations were using online conferencing software routinely and ten years ago it was still in its infancy. This in itself is a good example of how enabling technologies can simplify processes in ways that were never envisaged.

3. The 5-10-20-year vision for NDE in 2022

The full set of responses from the various participants can be combined and separated in many different ways to emphasise different aspects, but for the purpose of this summary they have been broadly classified under three themes: desired improvements in the capabilities of the NDE methods and techniques; asset-based challenges that need to be met; and aspects that deliver and help to realise the benefits of Industry 4.0.

3.1 Desired improvements in NDE capabilities

There are existing commercially available NDE methods that still fall short of the performance that is required by end-users for certain important applications. Some may be capable of being improved and research might already be underway to achieve the desired goals, while others might require a change of approach. Table 3 summarises the items identified in this category. In no particular order, some of the topics raised by the participants in the review are explained in the following paragraphs:

- Improved defect detection and sizing in 'difficult' materials. These include austenitic steel, high-nickel alloys, dissimilar metal welds and other coarse-grained and anisotropic materials. Ideally, inspections should become possible through rough, as-forged and dirty surfaces. Much progress has been achieved in recent years but such materials remain a challenge.
- Improved defect characterisation, especially of flaws that give rise to weak signals, such as stress corrosion cracking. The closure of

Table 3. Desired improvements in NDE capabilities

Topic	Estimated TRL in 2021	Five-year target	Ten-year target	20-year target
Difficult materials: improved defect detection in austenite, high-nickel alloys and dissimilar metal welds. Inspection through rough, as-forged and dirty surfaces	TRL 3-5	TRL 6-7	TRL 7-9	TRL 9
Improved defect characterisation: weak signal detection, more accurate sizing, use of non-linear UT, full matrix capture, etc. Stress corrosion cracking and creep cracking	TRL 3	TRL 4-5	TRL 7-9	–
Improved surface inspections: eliminate chemical-based methods, quantify effects of corners and edges on ET signals and simplify ET data inversion	TRL 3-4	TRL 4-6	TRL 6-9	TRL 9
Measure and monitor changes in material composition and properties: measure material properties such as composition, 3D microstructure, hardness, residual stress, fracture toughness, etc, and monitor their changes in service. Remote deployment ideally	TRL 1-3	TRL 4-6	TRL 7-8	TRL 9
Improved surface inspections: inspect whole area without scanning, accommodate complex geometries and eliminate human factors. Non-contact is an advantage	TRL 3-5	TRL 3	TRL 4-6	TRL 7-9
Improve near-surface inspections: extend to near-surface flaws (grey area between UT and PT/MT/ET), more reliable close-to-surface flaw detection and avoid manufacturing over-sized parts	TRL 2-3	TRL 4-6	TRL 7-9	TRL 9
Improve guided wave method: extend to more complex geometries, traverse multiple bends, traverse flanges and detect and size smaller defects	TRL 3-6	TRL 2-3 (flanges)	TRL 4-5 (flanges)	TRL 7-9 (flanges)
Improved mathematical models to support validation: need to be useable by a non-specialist with clear guidance on limitations. UT models regarded as mature but electromagnetic models still specialist	TRL 2-7 (TRL 9 in limited cases)	TRL 7-9	TRL 9	–

many high-temperature fossil-fuelled power plants in the UK has reduced the need for subsurface creep damage characterisation in pressure parts, but such methods would find a use in inspecting small and complex-shaped components, such as gas turbine blades.

- Surface inspections of large and complexly shaped components are another area for improvement. Traditionally, visual, penetrant and magnetic particle inspections have been applied to this task, but they can be slow to perform and in the latter two cases involve the transportation, storage and application of large quantities of chemicals, which represent an environmental hazard. Ideally, an inspection method is needed that can be applied to large surfaces without the need for other materials, can provide information on defect length and depth, can eliminate human factors and can provide a permanent record. Electromagnetic methods such as eddy currents appear to offer a solution, especially when arranged as arrays, but they are typically only used for niche applications, perhaps because their very versatility and complexity create a barrier for trainees. However, if signal inversion can be simplified or automated and the disruptive effects due to the proximity to edges and corners can be quantified and accommodated, then they will become more mainstream.
- Further developments that seek to measure material properties, such as the composition, 3D microstructure, hardness, fracture toughness, residual stress profiles, etc, and monitor their changes while in service, would also find a welcome place to supplement what are usually slow and destructive measurements. Steel and aluminium are the primary materials of concern. The capability to take the measurements remotely would be an added bonus.
- The capability to perform a whole area inspection without the time-consuming need to scan a sensor over that area has clear benefits for many industrial sectors. The ability to achieve this with a remote or non-contact sensor is a further advantage.
- Sometimes there is a grey area between surface and volumetric inspections that can lead to costs being incurred by industry. For example, visual, penetrant, magnetic particle and high-frequency eddy current inspections are used purely for the surface region itself, while a volumetric method such as ultrasonic inspection often has a dead zone of up to a few millimetres immediately beyond the surface, where defect detection is unreliable. A component could, in principle, enter service having a subsurface defect that has escaped detection if only inspected with a surface method or a near-surface defect in the dead zone of a volumetric method. To combat the near-surface dead zone problem, some components are deliberately manufactured a few millimetres over-sized and then machined to their true size after inspection. There is a desire to avoid this requirement by improving the near-surface capabilities of some volumetric NDE methods.
- Guided wave technology has been used successfully in many industrial sectors to locate and size defects in long lengths of pipes, rails, etc. However, there are calls to extend its versatility by applying it to more complex geometries, increasing the number of bends that it can traverse acceptably, and even to cross flanges. It is desired to be able to measure smaller defects than at present.
- Finally, there is an ongoing need to develop and refine models to assist the processes of inspection optimisation and technique validation. Great strides have been made in recent years to make software that is practical for use by a non-specialist, particularly in ultrasonic testing with packages such as CIVA, Pogo, PZFlex and other finite element models, but electromagnetic models still tend to need a specialist to run successfully. Improvements in the ease of use of mathematical models, coupled with clear guidance on their limitations, are regarded as essential tools for the developer of new inspections.

3.2 Asset-based inspection challenges

Much NDE is driven by an industrial requirement. Some inspection challenges might be long standing, such as the need to perform inspections in as short a period as possible to reduce plant downtime or to reduce the need for the removal of insulation, and others might be because of the introduction of new materials or because assets are operating in ways that were not envisaged when they were designed. Table 4 summarises the items raised by the industrial members and the following paragraphs give further explanation for some of the topics.

- The global cost of corrosion is US$2.5 trillion per year (approximately £2.2 trillion), equivalent to roughly 3.4% of the world's gross domestic product[7], yet the NDE thickness measurements that are used as a primary source of data are often acquired by entry-level ultrasonic technicians. This belies the complexity of the measurement operation and the range of conditions that are present in industry. It is anticipated that advanced signal processing techniques, perhaps involving artificial intelligence (AI), could be used to extract wall thickness values in cases where there is no clear signal, eliminating the risk of returning a null measurement in precisely those locations where corrosion is worst. There is also an ongoing need to scan large areas, faster and with high reliability, so that wastage trends can be measured accurately. Permanently mounted sensors that are capable of withstanding high temperatures, pressures and radiation would increase the range of components that could be monitored for corrosion. A further requirement would be the capability to measure wall thicknesses remotely, for example, from the annular skirt around the floor of a storage tank or underneath a pipe support.
- Many components are covered by insulation when in service and the cost of removing it to facilitate an inspection can often be many times higher than the inspection itself. NDE methods that can measure the underlying wall thickness but through the insulation would be a boon. Headway has been made using pulsed eddy currents but local corrosion regions can still be missed as the footprint is still relatively large. The detection of welds under insulation, and ultimately the inspection of those welds, would be a longer-term objective.
- Improved inspection through other types of coating, such as paint, magnetic, galvanised, conductive and radar/sonar absorbent is also desired. A related task is the inspection of the quality of the bond between a coating and the substrate. Other components are overlaid or clad with a protective material, which makes wall thickness measurements difficult to take. There is also a desire to be able to characterise any corrosion products that might lie beneath the protective barrier or insulation, perhaps using a non-invasive system for the detection of any generated chemical species.
- Reliable detection of blockages in pipes and tubes using non-invasive techniques would be welcomed. Some pipes can be inspected using pigs and low-frequency ultrasound can be propagated along the medium inside a pipe by placing a suitable sensor at an open end of a tube, but both require access to be provided in some form. It is desirable to be able to find blockages without having to gain entry or take a pipe out of service to do so.
- Traditional NDE has been applied to metals and in particular steel, but there are many different non-metals in use by the modern world that require inspection, where present methods are limited. The list is long but includes: polymers, such as high-density polyethylene (HDPE), composites and ceramics.

Table 4. Asset-based inspection challenges

Topic	Estimated TRL in 2021	Five-year target	Ten-year target	20-year target
Improved corrosion measurements: measurements when no clear signal, scan large areas, faster. Monitor over long periods (sensor reliability) and in harsh conditions (temperature, pressure and radiation). Accommodate internally overlaid and clad vessels. Characterise steel corrosion products	TRL 3-6	TRL 4-6	TRL 9	–
Remote measurement of corrosion: tank floor inspection from annular skirts and pipe walls at support structures. Improve detection, sizing and resolution	TRL 4-5	TRL 7-8	TRL 9	–
Inspection under and through coatings and insulation: inspect under coatings (paint, magnetic, galvanised, conductive, radar absorbent, etc). Quantification of bond quality. Detection (and inspection) of welds under insulation. Improve footprint of pulsed eddy currents. Non-invasive detection and characterisation of corrosion products	TRL 1-2	TRL 4-6	TRL 7-9	–
Detection of blockages in pipes and tubes: need a non-invasive system to locate blockages; inspection of non-piggable lines	TRL 1-2	TRL 4-6	TRL 9	–
Non-metal inspection: polymers, HDPE, composites, hybrid metal composites and ceramics. Monitor effects of radiation embrittlement, chemical attack, photo-oxidation and material changes. Quantify kissing bonds, bond integrity and weak joints. Need inspection methods for composite repairs, cable insulation degradation and wrappers (and underlying component through the wrappers). Mapping of internal structure and lay-up monitoring	TRL 1-2	TRL 4-6	TRL 9	–
Inspection of concrete: many civil engineering applications. Need to measure condition of concrete, for example thickness and spallation, as well as location and condition of rebars	TRL 1-2	TRL 4-6	TRL 9	–
Inspection in harsh environments: need to monitor defects at high temperatures in high-dose environments, for example waste packages, and in inaccessible environments, for example offshore wind turbines and subsea pipelines. Sensors need to be stable over many years	TRL 4 (sensors) TRL 1-2 (rest)	TRL 5-6	TRL 7-9	–

Requirements include the capability to monitor for the effects of chemical attack, radiation embrittlement and photo-oxidation; the characterisation of bond integrity, kissing bonds and weak joints; and insulation degradation and material changes suffered in service. It also includes the mapping of the internal meso-scale structure and monitoring the lay-up structure during manufacture. Other applications include the inspection of repairs that are made using wrappers and, of course, the ongoing need to inspect the component underneath the wrapper.

- An area that has not received much attention to date from RCNDE, but which nevertheless accounts for a significant proportion of the assets of several industrial members, is the inspection of civil structures such as chimneys, cooling towers, quays and jetties, turbine pedestals, radiation confinement structures, roadways, bridges and culverts, etc. Existing inspection methods for concrete tend to be short range and offer low resolution of any internal features, but there is an increasing need to monitor the condition of the concrete itself, for example for thickness and spallation, as well as to locate the position and condition of the internal reinforcement bars.
- The capability to be able to use NDE in harsh environments has always been a request from industry. These include at high temperatures (in static and rotating plant components), in high radiation dose environments, such as within nuclear waste packages, and in inaccessible environments such as subsea pipelines. In all cases, access for a human might become impossible, so the NDE sensors need to perform reliably for periods of what could be many years. Sensors that are stable over long periods are also required for a range of monitoring tasks in less stringent environments, for example the monitoring of structures for degradation in-service using structural health monitoring approaches.

3.3 Realising the benefits of Industry 4.0

When the previous vision was formulated in 2016[2], the terminology 'Fourth Industrial Revolution', often referred to simply as Industry 4.0, was seldom heard, but since then it has become more prevalent[8]. The fusion of digital and physical systems is finding applications in the home, at work and in wider society through products such as smartphones, autonomous vehicles, 3D printing and additive manufacture, materials science, nanotechnology, etc. Domestic products are available now that have built-in internet connectivity, the so-called Internet of Things. In principle, the use of AI and big data analytics will allow processes and infrastructure to self-organise, self-optimise and self-diagnose their status, so that larger commercial, safety and environmental objectives can be achieved. Additionally, NDE has a role to play in the development and growth of the circular economy, where materials that have reached the end of life in one function can be revalidated for use in another.

Improved NDE will play a vital role in Industry 4.0 as it provides much of the underlying data that is required (these advances are termed NDE 4.0[9,10]). It can do this in two ways:

- Advances in Industry 4.0 technologies leading to improvements in the way NDE is performed, for example by improving sensors, their resiliency in adverse environments, inspection reliability, data acquisition, data processing, visualisation, operator training, etc; and
- Advances in NDE 4.0 feeding back into industry to provide a greater volume of sensor data, higher data reliability, which in turn will ultimately lead to improvements in process control, plant optimisation, improved plant safety and reliability, etc.

To identify, prioritise and promote opportunities for NDE 4.0, the International Committee for Non-Destructive Testing (ICNDT) set up a Specialist International Group on NDE 4.0 in 2018, which is supported by a BINDT Working Group that has produced the following six key societal and business outcomes[11]:

- Improved through-life asset performance;
- More efficient production, including of new products;
- Better, faster and cheaper NDE, leading to a reduced cost of ownership;

- Efficient quality control for customised products (for example additively manufactured products);
- Reduced need for personnel in harm's way/travelling; and
- Efficient quality control for decentralised production.

During the update of the vision, the RCNDE industrial members have identified a number of areas that are important to NDE 4.0. These are summarised in Table 5 and described in the following paragraphs:

- To increase flexible working in organisations that operate assets around the world by optimising the deployment of a finite number of NDE personnel, there is a need to facilitate the remote acquisition of inspection data, automate and improve the real-time interpretation of that data, reduce errors due to human factors as far as possible and connect with other systems that store structural integrity and plant operational data. Data security and confidentiality will need to be maintained and the consequences of deskilling need to be understood. Furthermore, there will be a need to rationalise data formats to allow easy interoperability of equipment.
- The use of AI to help develop and optimise inspections is seen as a key benefit, but there are deep concerns about how such an approach can be validated and subsequently approved by an insurer or regulator when the data flows/processes that result in a solution are not fully understood, if at all. A best practice guide on how to use AI to validate inspections is needed.
- The use of augmented reality tools to help inspectors navigate around plant assets, position and scan sensors in the correct locations, recall NDE records belonging to previous inspections and retrieve supporting plant data, for example materials data and component histories, is needed. In addition, there is a requirement to assess the inspection data and upload it to a plant-level or component-level digital twin without undergoing a separate stage of producing an inspection report, then uploading that report to a larger system. Benefits are also seen in the use of augmented reality to support the training and accreditation of NDE inspectors.
- If NDE sensors are to be located on operating assets so that they can provide and upload data to a digital twin (at plant, process, product or part level) for what could be periods of years and possibly much longer, then, depending on the application, they will need to be able to survive high temperatures, high radiation exposure, repeated plant cycling events, harsh chemical environments, etc. During this time, their performance must not degrade, so reliability will be paramount.
- A key part of NDE is moving the sensors to the part that requires inspection and performing the measurement or scan. Traditionally, this has been achieved using a human operator, scanning frame, robot or a remotely operated vehicle such as a drone or submersible. In all of these cases an operator is needed either at the sensor or at a motion controller, or alternatively the scanning routes need to be preprogrammed. Autonomous systems that can be released and allowed to find the component to be inspected, cope with deviations from the expected and then carry out the inspection would find a use in many industrial sectors as they would drastically reduce the need for human involvement. Ideally, such systems would need to be able to find recharging points or harvest energy from the environment and, if operated as swarms, cope with malfunctions of part of the system.
- To facilitate improvements in manufacture, there is a growing need to be able to perform NDE inspections during the production of additively manufactured components, including the real-time inspection of welds that are produced in a manufacturer's works or as a repair on a plant. This avoids the wastage caused by the detection of flaws only after a part has been produced.

The realisation of these NDE 4.0 aims will necessarily involve an evolution of the roles and skillsets of the personnel who are involved. This was not raised explicitly during the updating of the vision but was a background theme for many of the participants. It was noted that a larger proportion of inspections will become automated or semi-automated and there will be less reliance on the interpretation of signals at the point of acquisition by a trained

Table 5. Industrial vision for topics relevant to NDE 4.0

Topic	Estimated TRL in 2021	Five-year target	Ten-year target	20-year target
Flexibility: remote assessment of data, real-time interpretation (in selected cases), security/confidentiality, rationalise data formats and understand consequences of deskilling	TRL 1-3 (TRL 9 in limited cases)	TRL 9	–	–
Improve inspection validation: test and optimise AI approaches, develop best practice for AI approaches, produce better defects (real and digital) in metals and composites, computer-aided design (CAD) models of defects	TRL 1	TRL 5-6	TRL 9	–
Automation/digitalisation: automated data analysis, faster interpretation, improved visualisation, reduce errors due to human factors and move to 100% digital inspections	TRL 1-3	TRL 3-5	TRL 6-8	TRL 9
Augmented reality: tools to assist more reliable inspections on plants, reduce errors due to human factors and improve training and accreditation of operators	TRL 2-3 (already TRL 9 in a few limited cases)	TRL 9	–	–
Improve inspection coverage: robots and drones, large-area inspection of pipework and vessels, scanner-less inspections, generic modular scanners, portable multi-axis robots, coping with dirty surfaces, high-temperature resistant and avoid dismantling plant to deploy	TRL 2-3	TRL 6	TRL 9	–
Autonomous inspection: using robots and drones (aerial and subsea) and multiple inspection bodies working as a team	TRL 2-4	TRL 5-6	TRL 7-9	TRL 9
Additive manufacture: NDE of 3D printed (bespoke) replacement parts in polymers and metals, wire arc additive manufacturing (WAAM) and powder bed fusion, monitor joining and machining operations during manufacture, in-process weld inspection, automation	TRL 2-3	TRL 6-7	TRL 9	–
Improve reliability and effectiveness of assets: integration with digital twin (comprising NDE, structural integrity and asset information), plant optimisation, self-diagnosing plants, early warning of problems and improved knowledge at fleet level	TRL 2-4	TRL 3-5	TRL 6-7	TRL 9

human operator, a process that can be tedious for the operator and make the final result vulnerable to inadvertent errors. There will be a greater need for personnel who can define, develop and validate an inspection system and who are comfortable with increasingly complex processes. Furthermore, they will need to work more closely with experts in related fields and have a deeper understanding of the objectives of the end-users to deliver the full benefits that are envisaged by Industry 4.0. The traditional Level 1, 2 and 3 roles will remain as a large number of inspections will continue for many years to come and will not need to be amended, but some further roles will need to be defined to reflect the changing skillsets and responsibilities that will become increasingly prevalent as the shift to the methods of Industry 4.0 gain traction. Discussions on what those new roles should encompass are already underway[9,12].

4. Summary

Much of the benefit of this update of the RCNDE vision is in the detailed requirements captured across multiple sectors, categorised and outlined in this paper. The higher-level messages, and the desired outcomes that drive the requirements, are clear both for the new Industry 4.0 vision and for the more traditional uses of NDE. Ultimately, advances in NDE, in combination with advances in other fields, will allow:

- Self-diagnosing plant facilities;
- Reduced disruption caused by plant breakdowns;
- Improved asset performance through life;
- Greater sharing of information about asset/component conditions across fleets, leading to plant optimisation;
- More efficient production, including of new products; and
- A reduction in the cost of asset ownership.

Since the previous review of the NDE vision, there has been more recognition that these objectives are attainable by exploiting the data produced by networks of sensors, systems and infrastructure, and through the combination of skills in different engineering disciplines. It is expected that the exploitation of machine learning and artificial intelligence, coupled with autonomous sensor delivery systems, will lead to novel inspection solutions being developed for many manufacturing and plant problems.

Traditional inspection problems will remain and almost inevitably there will be unforeseen plant breakdowns that will demand a rapid inspection solution, but in many cases the path to a solution is clear. Tools that will streamline the NDE solution-development process will be of huge value, as will the production of engineers having a broad range of skills and experiences.

The 5-10-20-year vision produced by RCNDE's industrial members will be used to shape the core research programmes and identify opportunities for new collaborations. It is planned to transition technologies into the field where they will provide benefits to the members through wider collaborations involving the Associate Members and other organisations. The vision will help to bring forward the application of inspection and monitoring technologies to meet future industrial needs and timescales.

References

1. P Thayer, 'RCNDE industrial members' vision for the future requirements for NDE', Insight: Non-Destructive Testing and Condition Monitoring, Vol 54, No 3, pp 124-127, March 2012.
2. P Thayer, 'Enabling the Fourth Industrial Revolution (4IR) and the role of NDE and monitoring', Insight: Non-Destructive Testing and Condition Monitoring, Vol 59, No 9, pp 469-472, September 2017.
3. BINDT, 'Report from the Workshop on NDT and SHM Requirements for Wind Turbines', Offshore Renewable Energy Catapult, National Renewable Energy Centre, Blyth, UK, 13-14 February 2019. DOI: 10.1784/report.2019.001
4. Website for the strategy of the Aerospace Technology Institute (ATI): www.ati.org.uk/strategy
5. Website for the National Manufacturing Institute Scotland: www.nmis.scot
6. Website for EPSRC Centre for Doctoral Training in Future Innovation in NDE (FIND): www.find-cdt.ac.uk
7. NACE International Impact Report, 'International Measures of Prevention, Application, and Economics of Corrosion Technologies Study', 2016.
8. Li Da Xu, Eric L Xu and Ling Li, 'Industry 4.0: state-of-the-art and future trends', International Journal of Production Research, Vol 56, No 8, pp 2941-2962, 2018. DOI: 10.1080/00207543.2018.1444806
9. R Singh and J Vrana, The World of NDE 4.0: Let the Journey Begin, 2021. ISBN: 979-8-4625-1421-0
10. N Meyendorf, N Ida, R Singh and J Vrana (eds), Handbook of Nondestructive Evaluation 4.0, Springer, 2022. ISBN: 978-3-030-73206-6
11. N Brierley and P Loftus, 'Roadmap for NDE 4.0 reveals breadth of challenges to be tackled', Insight: Non-Destructive Testing and Condition Monitoring, Vol 63, No 9, pp 522-524, September 2021.
12. M Bertovic and I Virkkunen, 'NDE 4.0: new paradigm for the NDE inspection personnel', In: N Meyendorf, N Ida, R Singh and J Vrana (eds), Handbook of Nondestructive Evaluation 4.0, Springer, 2021. DOI: 10.1007/978-3-030-48200-8_9-1