NDT SCOOP

QUARTERLY MAGAZINE

by ndtcorner.com

Proudly the Official Publication
NDT X EXPO 2025
26-28 AUGUST 2025 | CAIRO, EGYPT

ISSUE. 9 QUARTER. 1 (JAN. – FEB. – MAR.) 2025

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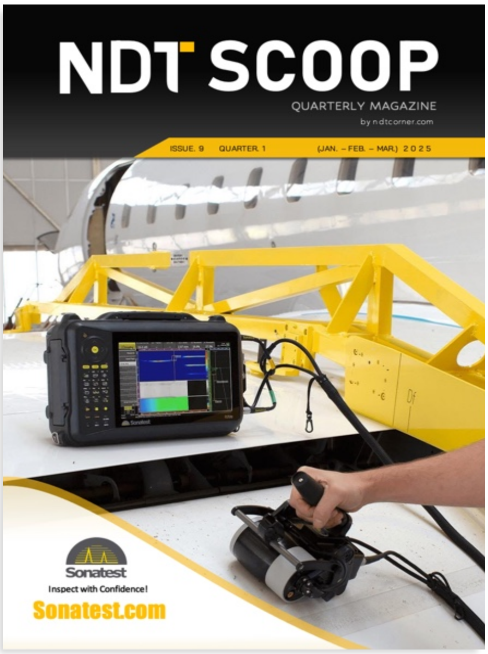

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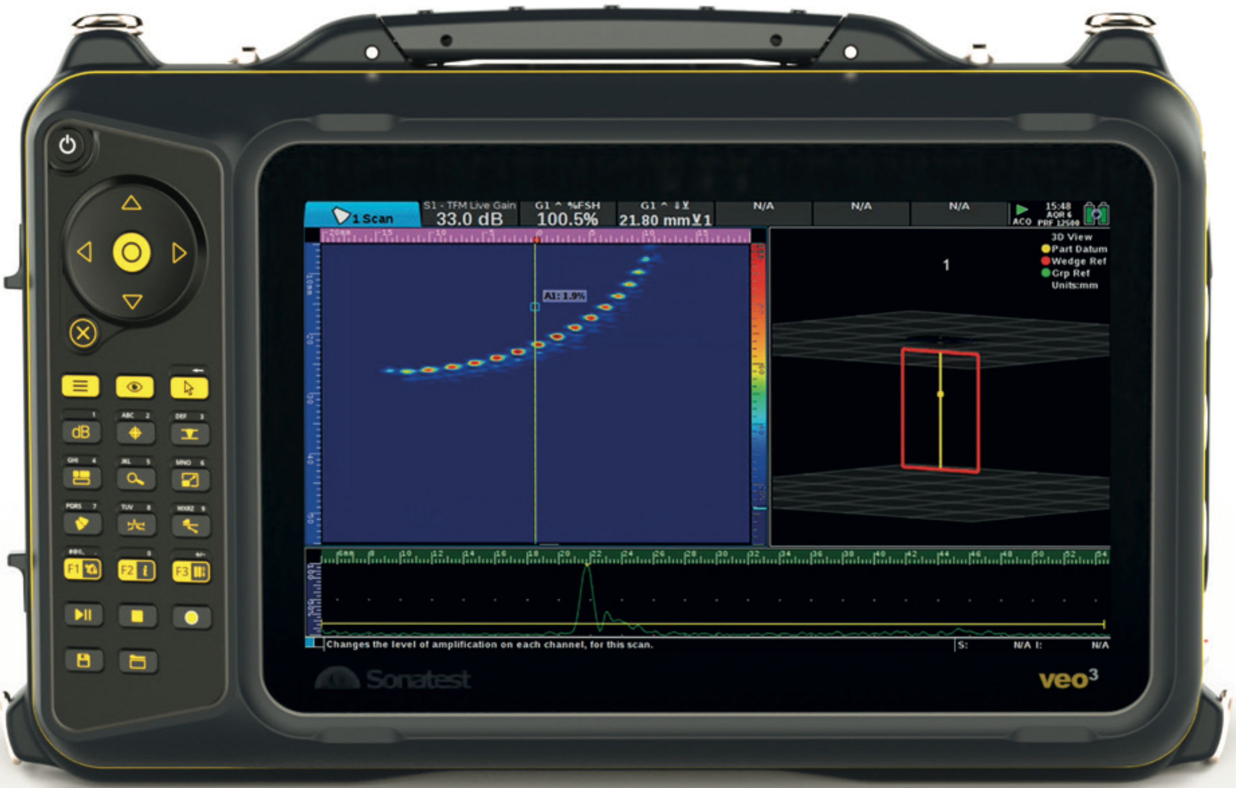

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Guideline for the Development of an NDE 4.0 Roadmap

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This paper provides a guideline to the various stakeholders of the **NDE ecosystem to develop a roadmap for NDE 4.0**. This paper provides the necessary support regarding HOW to realize the value propositions of **NDE 4.0**, which developed in earlier publications [1, 2, 3, and 4].

The Genesis of NDE 4.0

Historical Evolution

Historians identify three industrial revolutions since the second half of the XVIII century: mechanization (steam power), technical (electric power and mass production), and digital (computing and microelectronics).

The world of NDE has seen a parallel:
FIRST - tools to sharpen human senses,
SECOND - wave applications to view inside the components, and
THIRD - digital processing and automation.

As the industry goes through the **FOURTH revolution** powered by **interconnections and enhanced digitalization**, **NDE is also on a new horizon** with the addition of information transparency, technical assistance, machine intelligence, decentralized decisions, and much more.

The line between non-destructive evaluation (NDE) and the fourth industrial revolution is being blurred, since both are sensory data-driven domains. This multidisciplinary approach has led to the emergence of a new capability for non-destructive evaluation, now termed as NDE 4.0. ***The NDT community is coming together once again*** to define the purpose, chart the route, re-align the organizations, and address the adoption of emerging technologies.

NDE 4.0 is defined as a *Cyber-physical Non-Destructive Evaluation; arising out of a confluence of industry 4.0 technologies and traditional NDE physical methods, to enhance inspection performance, decision making for safety and quality assurance, as well as provide relevant data to improve the design, production, and maintenance* [1, 2].

The **fourth revolution** integrates the digital tools (from third) and physical methods of interrogating materials (from second) in a closed-loop manner reducing human intervention and enhancing inspection performance. Within the context of the physical-digital-physical loop of NDE 4.0 [3, 4]; digital technologies and physical methods may continue to evolve independently, interdependently, or concurrently. The real value is in the concurrent design of an inspection system through the application of Digital Twins and Digital Threads [3, 4]. This provides the ability to capture and leverage data right from materials and manufacturing processes to usage and in-service maintenance, creating value across the ecosystem [3].

Readers new to this subject are highly encouraged to use [1, 3, 4] as companion documents that provide the technical context in more than sufficient detail.

The ineluctable necessity of guidance

In [1] the digital technologies relevant to NDE were covered in a design thinking approach. In [3] the value proposition of NDE 4.0 for various stakeholders in the eco-system was discussed and in [4] the core technologies to enable NDE 4.0, like Industrial Internet of Things, Digital Twin, and Cyber-Physical Loops. Those publications covered the WHY and WHAT for NDE 4.0. An extensive description in the context of NDE has been published in the book "The World of NDE 4.0" [6]. The state-of-the-art in NDE 4.0 has recently been captured in the Handbook of NDE 4.0 [7]. All these publications create a nice vision of the future of NDE and a good indication of seemingly complex technologies. What is missing from the published literature on the topic is HOW to plan it out that makes business sense.

There is an extensive suite of digital technologies [1], and their impact is reasonably well understood as standalone pieces. However, their combination not only adds complexity, potentializing value generation but requires a deeper understanding. An increased bi-directional permeability of NDE and digital competencies in the workplace generating competency gaps that are real and have a profound impact, particularly at the union of digital and NDE skills. The two communities speak different languages, exhibit diverse demographics, learn differently, and more importantly have different viewpoints on technology adoption. A serious question today is - should you train an NDE expert on digital skills or an IT expert on NDE skills, while we wait for NDE schools to develop individuals on multidisciplinary competencies. The changing role of inspectors adds another level of complexity and resistance to the adoption of what can be hugely beneficial for everyone. An unsatisfied demand of highly specialized NDE technicians in specific niches runs parallel with the irruption and democratization of NDE technologies contained in digital direct-to-consumer products, such as IR sensors attached to mobile phones.

NDE, as a professional discipline, serves almost every industrial sector with infrastructure, and some of them are heavily regulated. Regulations inhibit transformation, provide friction to change, and need to be addressed if we were to leverage the digitalization of inspection processes. Quite often, the role of NDE is perceived to be a necessary evil and hindrance to operations. Thus, it gets relatively less attention during business investment decisions. The change agents, who can see the value in digitalization of NDE need help to overcome inertia and internal friction. They need tools to manage limited resources to unleash unlimited potential because NDE is transitioning from a niche role as a quality control support instrument to an invaluable knowledge-generating process able of creating significant value through substantial improvements in business sustainability, quality, and safety, that is why NDE 4.0 roadmaps are required to provide purpose and guidance for transforming the role of NDE in several regions of the world and industries.

The enormous leap in technology application and value realization tied to the fourth industrial revolution or digital transformation [8] can also be termed as massive transformation purpose (MTP). It is easier said than done. It requires leadership commitment, serious planning, and investment over a sustained period. It requires a roadmap that defines the HOW, starting with actions now and here. An explicit need for such a guidance has also been highlight by the recently formed Special Interest Group on NDE 4.0 (SIG-NDE-4.0) within International Committee for NDT (ICNDT). This paper provides a guideline to develop an executable roadmap for NDE 4.0.

Kickoff

Leadership Commitment

All transformation efforts begin with the identification of a leadership team, and it sustains as long as the leadership stays committed. To kick off an NDE 4.0 initiative, the organization must first identify a leadership team, that includes top executives and external experts, with oversight from Advisory Boards. There should be one champion to guide the roadmap development and execution. This champion needs to be passionate about safety and quality through inspections and supported by other leadership level team members including the finance, IT, and business development. The leadership team should quickly establish the following high-level items for the roadmap initiative.

Purpose

The leadership team should define and communicate the Massive Transformative Purpose (MTP) along with priorities for NDE 4.0. This MTP should provide a clear and aspirational point of reference to the intended roadmap initiative. This could be in form of enhanced safety, quality, reliability, performance, talent, technology, economic value, or sustainability through digital-physical integration. The NDE 4.0 purpose must align with the organization's primary business strategy. Several use cases were captured in [1,4]. Sustainable development and sustainability should be a consideration or constraint at the least.

This Purpose definition, in the form of an MTP, should consider the following attributes:

a) Grounded in sound engineering, science, and management principles
b) Being massive and aspirational in its scope
c) Must demonstrate a clear “why”
d) Clearly focused on large-scale transformations
e) Unique to the organization(s) or communities involved
f) Wildly aspirational to ignite the passion and unify the action.
g) Aimed at achieving profound transformations
h) Forward-looking

Eco-system Context

The context of NDE is anchored around the asset being evaluated, be it a single part under inspection in a manufacturing line or an infrastructure undergoing in-service maintenance. Any and every entity that comes in direct or indirect contact with an asset to assure its safety and quality can be thought of as belonging to the NDE eco-system. A typical representation is depicted in figure 1. Primary or core stakeholders (inner blue circle) have a substantial influence over the roadmap initiative. Support stakeholders (outer green circle) may or may not influence the roadmap initiative. Leadership needs to define the context for their organization. This figure has evolved compared to [3], in a spirit of continuous learning and improvement.

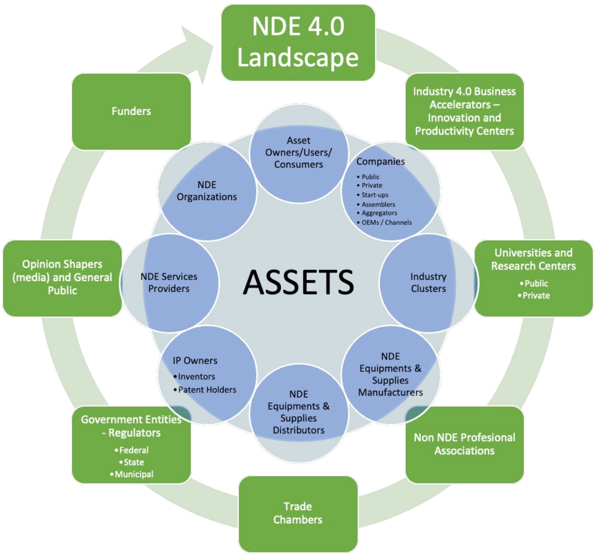


Figure 1: NDE Eco-system with ‘asset to be inspected’ at the center.

Vision

Once the leadership team has captured the context, it must establish a vision of a digitalized inspection system or a digitally transformed quality/safety assurance solution with a time horizon to accomplish the purpose. A good vision has many of the following characteristics:

Graphic and imaginable: Paints an accessible picture of the future, the organization strives for.
Compelling and inspiring: Moves people to act, igniting desire and personal connection.
Focused: Provide guidance in making decisions and allocating resources.
Feasible and realistic: Within the realm of resources and timeline, without undue stress.
Desirable: Indicates why the chosen path makes sense for the long-term interests of stakeholders.
Addresses triple bottom line growth – profit, people, and planet.
Simple: Brief, clear, easy to communicate and understand.
These characteristics also flow down to the roadmap.

Policy

The leadership team should develop and implement a digital transformation policy if it does not already exist. The policy should

Demonstrate commitment to digital transformation strategy, objectives, and activities.
Define the purpose and context for digitalization in support of its strategic direction.
Provide guidance with conflict resolution, resource prioritization, and escalation.
Support human development, re-skilling, and new competencies integration.
Balance the human-machine co-working, keeping each one in areas they are best at.
Consider eight innovation management principles, described in ISO 56002.
Show commitment to ethics, sustainable development, and continual improvement.

The digital transformation policy should fit the organization's culture. The policy should be circulated as documented information to all key stakeholders, including employees, contractors, and relevant external interested parties, as appropriate. The ethics portion of the digital transformation policy may be integrated with an existing ethics policy or code of ethics, and prominently displayed in common areas.

Roadmap Team

With clarity of purpose, context, vision, and policy, the leadership team should identify individuals who should develop and maintain the roadmap. The Roadmap Initiative Team (RIT) should be knowledgeable about digital technologies, inspection methods, data sciences, business models, and human considerations. The leadership team should define the charter for the roadmap team. For a small business, the leadership team can be the roadmap team, or leverage consultants and partners.

Framework

With leadership commitment as evident from the purpose, vision, preliminary external context, and charter, the RIT is ready to get to work and create the roadmap. Just to be on the same page; a roadmap is a "Document that visually describes the activities, timeline, and resources necessary to achieve a strategic objective, such as digital transformation in case of NDE 4.0" and a Roadmap Initiative is "an internal effort by a dedicated team to create the roadmap and keep it current."

Context

The RIT must define the context along three dimensions with reasonable details and confidence.

The internal context of an NDE 4.0 deployment refers to all elements that lie within the organization, and can be controlled by the leadership, as primary elements of the roadmap, to pursue strategic objectives. It includes products/service offerings, business models, technology portfolio, intellectual property, infrastructure, physical assets, data assets, employee skills, competency gaps, human factors, diversity-equity-inclusion, code of ethics, financial capacity, risk tolerance, partnerships, geographical location, and to some extent preferred suppliers and consultants.

The external context of an NDE 4.0 deployment refers to all elements that lie outside the organization and cannot be controlled by the leadership. The roadmap should provide guidance to continuously monitor the external context and to modify the internal context in response to any changes in the external context. Industry 4.0 or Digital Transformation is the key external driver for the emergence of NDE 4.0. External context includes all the stakeholders in the ecosystem that were not a part of the internal context. The most significant are the market forces within the sector – customers, competitors, and regulatory bodies. It also includes changes in political, environmental, social, technological, economic, legal, Innovation, and pandemic aspects (PESTEL+I+P), that are even broader than discipline of inspection or the industrial sector. With globalization, one needs to consider global trends, even if the internal context is geographically local.

The prospective context of an NDE 4.0 deployment refers to internal and external elements that will emerge over the future whether controlled or uncontrolled. The roadmap should provide guidance to continuously monitor the evolution of desirable, anticipated, and unanticipated items and to modify the internal context towards the desirable prospective context. The core of the roadmap is that portion of the prospective context which includes planned development of products/services, technologies, talent, physical and intellectual assets, and resiliency. Prospective context should also consider items broader and far-reaching than business. Such as professional obligations, ethical awareness, industry regulations, social responsibility, sustainability, and sustainable development. A simple well-articulated prospective context can be indistinguishable from vision.

Principles

It is now time for RIT to agree on principles keeping the purpose and context in mind. Here is the starter list derived from Industry 4.0 principles [9]. These principles should guide the team in the selection and development of products, technologies, and competencies.

Interoperability: The ability of assets, instruments, sensors, devices, inspection equipment, and people to connect and communicate with each other via (IOT)

Information transparency: The ability of assets and inspection systems to share information (data with semantic interoperability), facilitating interpretation, training, and visualization.

Technical assistance: The ability of assets to assist in workflow management, inspection automation, and traceability

Decentralized decisions: The ability of automated cyber-physical inspection systems and assets to make decisions on their own and perform inspection tasks independently; or to seek human intervention in the case of exceptions, interferences, or conflicting goals.

Virtualization: The ability of assets to generate virtual models of themselves and of other assets in their environment that facilitate the generation of digital-twins.

Real-Time: The ability of assets to generate datasets that may be retrieved in real-time to support and substantiate decentralized decision-making processes.

Modularity: The ability and design characteristics of assets to flexibly adapt to different requirements.

Product-Service Offering: The ability of NDE 4.0 solutions to synergistically merge products and services to create, capture, and distribute substantially enhanced value in order to achieve the purpose of NDE 4.0

Governance

The leadership team is responsible for the overall governance of digital transformation, which is a little different than traditional governance approaches. A well-governed NDE 4.0 program must satisfy different stakeholders across an organization and be flexible enough to accommodate multiple types of initiatives while ensuring enough rigidity to achieve strategic alignment with purpose and efficiency in execution.

The following principles should be considered while identifying initiatives that go into the roadmap [10]

a) Centralize information about digital initiatives rather than the initiatives themselves.
b) Move from centralized to decentralized governance of digital initiatives as digital maturity grows.
c) Decentralize ideation but centralize idea evaluation and prioritization.
d) Make sure that KPIs and Metrics measure the real impact you want to achieve with each initiative.
e) Avoid siloed solutions by ensuring data compatibility, technical consistency, and continuous integration of new initiatives with existing systems.
f) Implement a “fit-for-purpose” mapping system that recognizes value potential and degree of feasibility for each initiative.
g) Evaluate different scenarios to proactively steward digital initiatives toward full-scale impact.

These principles are in addition to whatever governance system is in place for everyday operations addressing the use of internal standards, alignment with international standards, risk mitigation, transparency, relationship with stakeholders, internal and external communication, chain of command structure, and policy deployment.

Ethics

Any transformation roadmap must include instances and guidance devoted to providing sound ethics foundations to all the categories included in it. The leadership team is encouraged to engage an external expert on ethics in digital transformation, as the subject is still evolving. This ethical dimension must be an integral part of the governance and aligned with the attributes specific to humans, and human-machine integration.

There are five fundamental considerations on the human side of ethics:

Responsible: The accountability of all instances involved in the digital transformation should be clearly established in the organizational operations.

Equitable: All organizational and individual participants should have equal access to the instances and support resources that constitute the ethics foundation of the roadmap initiative.

Traceable: Accountability for decisions and actions should be clearly established. Records should be generated to properly support any traceability requirements.

Reliable: The reliability of ethical implementation should be sustained by codes and guidelines, personnel training and auditing, and an ombudsman program.

Sanctions: Ethics code and guidelines once established should have clearly defined instances, processes, and resources to positively inhibit and sanction ethical behavior violations.

These five considerations are altered in the context of the Human-Machine side of Ethics, where the machines learn and act autonomously, such that the machine output is not entirely in human control.

Responsibility: NDE personnel will exercise appropriate levels of judgment and care while remaining responsible for the development, deployment, and use of AI/ML in NDE capabilities.

Equity: The digital inspection system developers will take deliberate steps to minimize unintended bias in AI/ML-based NDE capabilities.

Traceability: The AI/ML capabilities will be developed and deployed such that relevant NDE personnel possess an appropriate understanding of the inspection technology, development processes, and operational methods applicable to AI capabilities, including transparent and auditable NDE methodologies, data sources, inspection procedure, and documentation.

Reliability: The AI capabilities will have explicit, well-defined uses, and the safety, security, and effectiveness of such capabilities will be subject to calibration, validation, and POD assessment within those defined uses across their entire life cycles.

Governance: The digital inspection system developers will design and engineer AI capabilities to fulfill their intended functions while possessing the ability to identify and avoid unintended consequences, and the ability to disengage or deactivate deployed systems that demonstrate unintended behavior.

Data Management: The NDE personnel will honor the data acquisition, transfer, storage, analysis, processing, security, and ownership/sharing rights as determined by organizational policy and contractual obligations. The leadership team also needs to communicate ethical considerations to all employees, periodically.

Roadmap

Scope and Objectives

The scope of the NDE 4.0 roadmap could be the development of one or more of the following applications depending upon leadership purpose and vision.

Digitalization of NDE (Or Industry 4.0 for NDE): Initiatives directed at the application of Industry 4.0 principles, technologies, and frameworks to improve and expand the realm of NDE solutions in the world. For example: Autonomous drone/robotic NDE for bridges, towers, pipelines; and Digital RT/UT/ET along with Augmented Intelligence for integrity assessment of in-service high-risk assets, such as Turbine parts.

NDE for Digitally Transformed Systems (Or NDE for Industry 4.0): Initiatives directed towards establishing NDE as one of the major data sources for Industry 4.0 needs, pains, and gains [3]. For example: Digital RT/UT/… for an additively manufactured to gain feedback regarding the manufacturing process or Manual UT/ET with digitalized reporting at the end to fuse the data with the data of an automated manufacturing line.

Fully Integrated NDE 4.0 and Industry 4.0: Initiatives directed at integrated development of digitalized NDE capability within digitally transformed systems to fully deliver the promise of Industry 4.0. For example: NDE technologies integrated within smart manufacturing for inline quality assurance with no human intervention; In-situ real-time NDE within additive manufacturing process to control the process for part quality assurance; or NDE and SHM digitally fused to assure service performance and safety.

Planning Horizons

Based on the purpose, vision, scope, and objectives; and the rate of change in the external context, the roadmap team can define three planning horizons,

Horizon-1 (Operational or H1): This includes projects and initiatives to bring tangible value in a "now and here" timeframe. These tactical-term projects and initiatives may be 3 to 24 months in duration. It is important that H1 initiatives are fully funded through completion.

Horizon-2 (Strategic or H2): This includes projects and initiatives to bring tangible value in a "Near future, embracing emerging trends" timeframe. These strategic-term projects and initiatives may be 1 to 5 years in duration. Strategic-term projects and initiatives are intended to generate and capture significant stakeholder value when implemented. H2 initiatives may have proof of concept or demonstrator technologies identified and funded under H1.

Horizon-3 (Visionary or H3): This includes projects and initiatives to bring tangible value in a "Pursuit/tracking technology evolution in line with purpose" timeframe. These long-term projects and initiatives may exceed a period of 3 years. These should address ambiguity and uncertainty, particularly in an external technological context. H3 Initiatives may have demonstrators identified under H2 and exploratory studies funded under H1.

Leadership must assure alignment and continuity of H1, H2, and H3 outcomes through funding mechanisms.

Caution: The three-horizon model when applied to transformation or any significant change, needs special care because it is hard to see clearly that far. The H2 and H3 planning carries a significantly higher level of uncertainty and will likely require major modifications and pivots, both technological as well as business models, as it evolves.

Dashboard

The leadership team should identify a set of KPIs and metrics, in an integrated dashboard or scorecard, aligned with the MTP. The performance should be monitored by the leadership. These KPIs should cover the four prominent categories in line with a balanced scorecard viewpoint.

Value Creation perspective: These are tied to the internal processes supporting the primary purpose of implementing NDE 4.0. It could be in terms of performance, safety, capability, reliability, speed, workflow efficiency & effectiveness, accelerated learning and certification experience, Asset design improvement, asset quality, waste reduction, etc.

Customer perspective: These are tied to the value delivered to the customer – enhanced safety, turn time, cost of operations, etc.

Employee perspective: These are tied to renewed respect for NDE, employee learning and development, as well as improved inspector safety and support.

Financial perspective: This is the traditional quantification of impact on top line and bottom line. This most popular set of metrics should not be looked at in isolation, but through the natural and profound interconnection with the other three perspectives.

In addition, one may choose to add tracking of strategic progress and risk management as add-ons. Ineludibly, all MTPs and metrics defined for roadmap initiatives should take into consideration any human perspective of NDE 4.0, including ethics.

H1 initiatives should have tangible and definable metrics. H2 initiatives should have a measurable metric without a target assigned. H3 initiatives should not have any measurable goals, other than total investment limits. The KPIs represent quantitative or qualitative parameters that show how effective are the operations in achieving the objectives. Metrics represent quantitative or qualitative parameters that serve to monitor the status of any specific process.

Draft Roadmap

Roadmap essentially constitutes a custom portfolio of technologies and enabling initiative, specific to the target markets – including industries and geographical regions. It should consider the following elements:

(a) **Synergistic planning horizons**: Proper balance and blend of H1/H2/H3.

(b) **Digital technologies readiness**: Based on technology adoption curves and technology surveillance process for the state-of-the-art in R&D and practical applications.

(c) **Smart workflows**: Integrating devices and communication protocols to accelerate the value generation process.

(d) **Smart NDE Applications**: AI permeation or readiness for AI should be a part of the technology portfolio.

(e) **ICT infrastructure**: should be specifically addressed as one core element in any roadmap deployment initiative.

(f) **Decision support systems**: Technologies that generate relevant knowledge to support decision-making processes should constitute a desirable element in a technology portfolio. Dashboards and scorecards with adequate UX design and relevant KPIs may serve as interfaces to guide and facilitate those decision-making processes at all relevant instances.

(g) **Pilot programs**: Devoted to field validation of innovative solutions to decide which ones can be refined and which ones should be pivoted.

(h) **Deliberate frequent reviews**: which can be built in as an integral part of activities to account for uncertainty in planning, execution, and outcomes; and create opportunities for revisions at a frequency higher than the normal strategic cycle.

Based on the diverse requirements of the NDE domain, the landscape of technologies discussed is graphically shown as a mind map in figure 2. Industrial Internet of Things (IioT) and Digital twin are at the core. They connect, manage, import, and export data across various technologies and applications through data acquisition, managing, processing, visualization, and physical action.

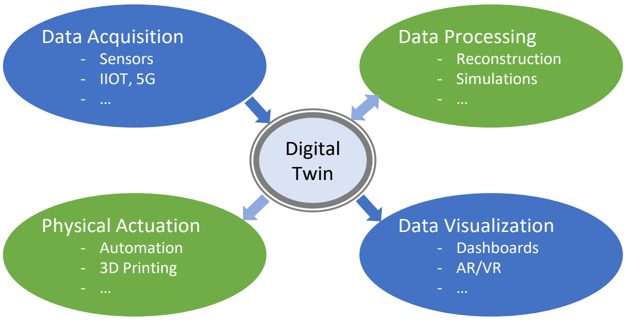


Figure 2: Mind map for NDE 4.0 technology landscape [6]

Data Acquisition and Handling includes Industrial Internet of Things, Digital twin, thread, and weave, Semantic interoperability and ontologies, 5G, Blockchain, Data security and Sovereignty, Data integrity, Traceability, Revision safe data formats and storage, Data Transparency, etc.

Data Processing and Computing includes Big Data, Cloud Computing, CAD/CAM/CAE/BIM, Simulation, Reconstruction, and inverse engineering, Smart Handheld devices, Edge Computing, Quantum computing, Artificial intelligence, Machine Learning, Deep Learning, Generative AI, Algorithms (heuristic, model-based and statistical), Image analysis/signal-information-raw data processing, Sound analysis/signal-information-raw data processing, etc.

Data Visualization includes Extended Reality (AR/VR/MR/PR/XR), Dashboards, Volumetric Displays, etc.

Physical Actuation, includes Automation, robotics, drones, Automated Inspection Systems, Additive manufacturing, etc.

In addition to these, the RIT must consider need for **Enabling Hardware,** such as: Special Hardware for AI, Telepresence, Biodegradable sensors, DNA Computers and Storage, Smart Dust, Neuromorphic Hardware, Carbon-based transistors, Nanotube Electronics, Customized analog/digital sensor development, etc.

Vertical and Horizontal Human-Systems integration of all these requires the inclusion of Virtual Personal Assistance – Conversational, Gesture, Smart workspaces and UX Design, Interface Layers and Standards, Brain-machine interfaces, Responsible AI, Intelligence augmentation and Machine assisted decision making, Cryptography, (Symmetric-key, Quantum, Public-key, Post-Quantum)

RIT should not discount the role of **new protocols and interfaces**, and any **new regulatory constraints**.

Roadmap Validation

Every roadmap needs validation. This is a two-step process.

Internal Validation comes in form of a review of the roadmap conducted by the leadership team and grounded in past experience. One of the possible ways is to view the alignment in inverse order, initiating with the learning and growth, and moving upward toward the financial perspective. Another is to play what-if scenarios. Third could be cross-check with historical performance or know-how of the advisory board.

External Validation requires engaging with key external stakeholders. One possibility is to engage with trusted customers on what-if scenarios. Another one is benchmarking with non-competing organizations.

Supplementary insights to improve the roadmap content may include a) Team structure, roles, and membership expertise, (b) Sponsorship and funding requirements including number, profiles, and amounts to be obtained, (c) Inclusion of specific initiatives under current R&D activity to improve their alignment with MTP, (d) Supplementary partnerships or alliances, and (e) NDE 4.0 Ethics Check.

Execution

Now the rubber meets the road. RIT must execute according to the validated roadmap with the realm of principles agreed upon with the leadership team.

Resource Allocation

Leadership commitment essential to support NDE 4.0 for it to be successful, is exhibited through the allocation of resources and progress reviews. Leadership should be prepared to provide resources, further development of new skills and competencies, as well as new tools and methods. These resources are categorized as follows and should be identified in the roadmap.

General Resources: This refers to all tangible resources excluding people.

(a) **Financial**: Funds the projects and activities, which may come from internal or external sources.
(b) **Partners/suppliers**: Support network with capabilities that do not exist in house.
(c) **Infrastructure**: Tangible or intangible assets for installation, operation, and deployment of projects or initiatives. This includes (i) physical equipment and systems, (ii) digital devices and systems, (iii) information systems, and (iv) communication.
(d) **Equipment**: Tangible assets required to develop the required knowledge and technologies in support of the projects and processes. IOT-enabled equipment should be preferred over stand-alone units.
(e) **Technologies**: Access to a portfolio of proven fundamental technologies for developing prototypes. Annexure-C provides a starter list.
(f) **Knowledge**: Know-how and know-why of existing products/technologies in a documented form.

Human Resources: This refers to people with relevant skills, competencies, mindset, and capacity to support the roadmap [11,12].

Skills refer to a person's ability to perform a certain task, such as an NDE UT practitioner's skill to scan a weld using a phased array transducer within a pressure vessel. Skills may be classified as:

(a) **Trade Skills** (or Hard Skills): They provide the foundation for the deployment of NDE 4.0 projects and initiatives. They include (i) NDE-specific physics, (ii) General Science and Mathematics, (iii) Electrical, mechanical, and systems engineering, (iv) Technology integration & application.

(b) **Digital Skills**: They provide the capability to integrate commonly available digital systems with foundational NDE systems. They include using devices and handling information, programming, creating, and editing digital content, digital communications, digital transactions, and online security.

(c) **Data Skills**: They provide the capability to establish data organization and reliable statistical and deterministic data processing. commonly available digital systems with foundational NDE systems. They include converting data to information, fusing information, and training artificial intelligence solutions.

(d) **Soft Skills** (or people skills) – They allow improved performance both on an individual basis and as a workgroup to manage a project or initiative successfully. They include: (i) Mindsets - self-awareness, character traits, and attitudes; (ii) External relations - social awareness, team effectiveness, interpersonal people skills, social skills, communication skills, career attributes, emotional intelligence skills, and responsible online behavior (iii) Management Skills - planning, communicating, decision-making, delegating, problem-solving, conflict resolution, motivating and negotiating (iv) Balancing and blending human-machine coworking at both physical and intellectual levels.

Competencies refer to the capability of applying or using knowledge, skills, abilities, behaviors, and personal characteristics to successfully perform critical tasks, specific functions, or operate in each role or position (See figure 3). Competencies are thus underlying characteristics of people that indicate ways of behaving or thinking, which generalizes across a wide range of situations and endure for long periods of time. Performing the role of an NDE Level III to manage all NDE-related processes within a company is an example of a competency.

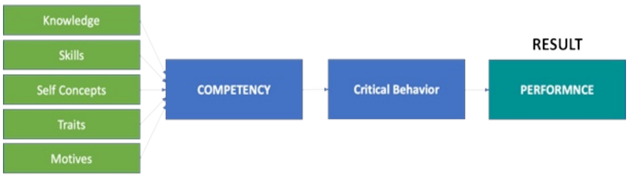


Figure 3: Performance depends upon several factors [13].

The roadmap team should identify roles and their description with all relevant skills and competencies necessary to perform it successfully in the context of the roadmap initiative. These role descriptions should be integrated by each operative area and aligned with the objectives of the roadmap, validated by the leadership team. A role often missed is that of a Chief Engineer, who acts as a systems integrator and understands technology, application, and evolutions. The role may not be necessary but, it helps significantly to have a technical focal at the leadership level. Once those role descriptions are established and validated, a gap analysis should be performed for everyone assigned to the role to define his/her development plan.

For specific projects and initiatives, the completion of particular certification(s) may be required. Those requirements should be identified and integrated into the consolidated training program where there is an already available certification program. For certain instances, where no generalized certification programs are available, the development of a tailor-made certification program should be considered, or a well-documented exception justification by appropriate stakeholders.

Technology Management Process

Projects and initiatives on the roadmap should be managed with rigor of technology or innovation management depending upon the degree of uncertainty. The steps include:

a) **Technology surveillance/vigilance**: The search in the environment for signals and indications that allow the identification of threats and opportunities for technological development and innovation. This may include benchmarking, Markets/Customers research studies, and technological monitoring.

b) **Technology planning**: The development, review, and revision of a technology portfolio that allows the organization to select lines of action to achieve a competitive advantage.

c) **Technology alignment**: The organized integration of technology in all the organization's operations. It also includes the alignment of the technology plan with the business strategy.

d) **Technologies and resources enablement**: The procurement, inside and outside the organization, of technologies and resources necessary for the execution of the projects in the portfolio. This may include a) Technology acquisition (purchase, licensing, alliances, and other applicable methods). b) Technology assimilation, c) Technology development (technological research and development, technology up-scaling, and other applicable instances), d) Technology transfer, e) Technological projects portfolio management, f) technology-involved personnel management, g) financial resources management and h) knowledge management.

e) **Technology patrimony protection**: The safeguarding and care of the organization's technological patrimony, generally by obtaining intellectual property rights. This includes activities intended to capture, transform, protect, and preserve the intellectual property generated.

f) **Technology deployment**: The implementation of innovation projects until the final launch of a new or improved product/service/experience to the market, or the adoption of a new or substantially improved process within the organization. It includes the commercial exploitation of such innovations and the organizational expressions that are developed for this purpose.

NDE 4.0 also requires significant innovation management which entails a matchmaking between needs and ideas. Guidance for innovation management can be found in ISO 56002 [14] and Innovate Pedia [15].

Operations

Operations enable the transformation of intentions and plans, into securing resources, to produce verifiable results. An organization may already have them in place and should be able to use as many of the existing processes as practical. All processes to facilitate digital transformation should align with success metrics (KPIs) defined under the primary dashboard perspectives.

Financial: These processes manage the generation and use of funds that make the digital transformation viable. Financial management may include, but is not limited to:

(a) **Data monetization**: that allows a business proposition around the transfer of data.

(b) **Portfolio approach**: for aggregation and diversification of investment portfolios.

(c) **Intangible assets**: generation, maturity, integration, and protection for a competitive edge.

Customer: These processes manage the relationship with the most significant stakeholder group, to obtain the intended outcomes of the roadmap initiative. Customer relationship management may include, but is not limited to:

(a) **Customer insight**: through continuous empathic feedback intended to capture valuable insights for improvement of (i) the roadmap and resulting value creation for the customer, (ii) relationship, and (iii) internal processes for value creation.

(b) **Impulse value generation perception**: using communication processes intended to close the perception gap between the true and perceived value delivered, aimed at minimizing the risks for the deployment and adoption of the roadmap initiative.

(c) **Customer education**: to provide support through the guided diffusion of knowledge, skills, and competencies and facilitate the deployment and adoption of the roadmap initiative.

Value Creation through internal processes: These processes enable the creation, capture, and distribution of value to satisfy stakeholders' needs, including customers, and meet business strategic goals. Value management may include, but is not limited to:

(a) **Value chain management** is the basic traditional approach to the creation, capture, and distribution of value and is at the core of almost all management perspectives.

(b) **Value network management** expands the value chain management to a wider ecosystem, and how tangible and intangible value is managed through knowledge sharing, sometimes in real-time.

(c) **Technology management**: as described above.

(d) **Ideation and Innovation Management**: process and techniques at the core of design-thinking initiatives to stimulate creativity and value through novelty.

(e) **Validation/Qualification**: constitute the assurance that processes, systems, facilities, equipment, and people contain the elements required to properly perform their functions.

(f) **NDE-specific processes**: starting from the data acquisition through sensors, networked within NDE systems, that provide information from assets, and their environment, and enable decision making.

(g) **NDE certifications**: which guide validation and provide evidence that NDE systems and personnel have the necessary competencies based on standardized certification requirements, (such as ANSI/ASNT CP-189, ISO 9712, etc,) or based on industry/company/application specific requirements.

(h) **Regulatory compliance**: with all the applicable regional legislation and industry-specific requirement within the roadmap scope, monitored continuously, and used to update the portfolio and so it is always relevant and useful.

Learning and Growth: These processes help formulate and implement the development of human resources and organization knowledge base - the intangible assets of the organization to support value creation. Learning management may include, but is not limited to:

(a) **Talent management**: from the development of individual skills and competencies, and organizational career tracks, to succession planning, including incentives to retain and reinforce talent.
(b) **Knowledge management**: from development and containment of documented know-how and know-why, including procedures, and databases, to performance and organizational learnings.
(c) **Continuous improvement**: seeking to improve every process by enhancing the activities that generate the most value for the stakeholders, while removing waste. It completes the value creation loop that transvers the four perspectives

Risk and Uncertainty Perspective: These processes help assess and mitigate risk in technology development and market capture. Risk mitigation may include, but not limited to

(a) **Portfolio Management**: as discussed above
(b) **Technology reviews**: using a phase-gate process with competent experts as gate keepers.
(c) **Marketplace benchmarking**: to assess the needs, gaps, and competitive position.
(d) **Customer-shared vision**: to assure certain market share and investment recovery.

Roadmap Diffusion

The roadmap needs acceptance across the organization and communication to relevant external stakeholders. This requires structured communication to promote and garner support for success.

Internal Diffusion refers to topics within the organization, where the leadership team has a relatively higher degree of control.

(a) **Overcoming internal barriers**: such as adverse organizational culture, inadequate organizational structure, internal politics, attitudes, or communication barriers. Analysis tools such as force-field diagrams may be used to identify and prioritize actions.
(b) **Transparency**: through mechanisms aligned with the purpose of the roadmap initiative and in adherence with applicable company policy on information sharing.
(c) **Authority and autonomy**: to execute specific activities as deemed essential for success.
(d) **Employee engagement**: through communication, alignment of personal growth with company growth, incentives, and inclusion in decision making.
(e) **Teamwork engagement**: through an environment of mutual trust among engaged employees.
(f) **Ownership commitment**: as demonstrated through their personal involvement in the roadmap**.**

External Diffusion refers to select engagement with external elements through networking and influence. The roadmap communication strategy should integrate an analysis of all relevant stakeholders in order to properly diffuse the messages to each type of stakeholder and prevent adverse impacts to the roadmap initiative derived from the action of ill-intentioned social agents.

(a) **Overcoming external barriers**: such as legal, regulatory, market perceptions, industry level politics, IP rights, etc.
(b) **Go to Market**: strategy with limited exposure of the roadmap to select customers.
(c) **Marketing, diffusion, and adoption**: strategy to capture share early.
(d) **Customer engagement**: to capture their requirements and improve their utilization of your products/services.

Regulatory engagement: An early and active participation in relevant regulatory instances is strongly recommended to guide and positively influence the evolution of regulatory elements relevant to the roadmap scope.

Improvement

The roadmap must continuously improve to fully capitalize on opportunities and minimize risk. This requires a periodic performance evaluation of leadership, planning, support, and operations, with full awareness of changes in external and internal context, and reassessment of prospective context. This can be achieved as follows.

Acceptance

Information and knowledge required to evaluate the acceptance of the roadmap should be regularly compiled and analyzed. This information and knowledge may take the following form:

(a) **Massive Transformation**: performance as noted by KPIs, and metrics aligned with the Massive Transformative Purpose and scope, as well as stakeholder feedback on progress.

(b) **Full KPI dashboard**: with quantitative parameters for the objective performance assessment of various processes categorized under Business or ESG KPIs and metrics.

(c) **Barriers and limitations**: that impede the advancement of roadmap initiatives should be identified, documented, and addressed adequately.

(d) **Organizational structure:** that constrains the execution of the roadmap should be identified and addressed.

(e) **Resource constraints**: that limit the execution of the roadmap should be identified and addressed.

(f) **Setbacks and Failure**: when properly focused by leadership constitute important opportunities to derive learning processes and to generate improvement opportunities.

Analysis

Roadmap deployment, review, and changes should be data-based. The leadership Team should implement and institutionalize a structured analytical approach to process and analyze the KPIs and metrics.

(a) **KPI Analysis**: of data captured on pre-determined items over a period. It includes Business indicators, and ESG/SDG indicators. The analysis may include causality validation, context validation, benchmark validation, or segmentation validation.

(b) **Root cause analysis**: of KPIs, their trends, or unintended discrete events to support any decision-making process derived from it.

(c) **Impact scope analysis**: to deeply survey the KPIs and metrics for value created by roadmap. The impact can be analyzed from two perspectives – business value and social value, even if they go in opposite directions.

(d) **Trends and projections**: using appropriate numerical methods, statistical analysis methods, and algorithms to generate projections and improve planning processes.

(e) **Scenario-based forecasting**: for critical to business KPIs, to generate response protocols and contingency plans. Uncertainty may be accounted for by making estimates from conservative and aggressive assumptions.

(f) **Best practices spotlight**: that support the roadmap development, execution, and diffusion; from internal or external sources. Note: Best practices do not imply that they are not subject to improvement.

Review

Review complements the analysis to extract the necessary knowledge and decide on actions for improvement and sustainability of the roadmap initiative. The review process should consider, but not be limited to:

(a) **Periodic reviews**: at a frequency predetermined by the leadership team, with a formally defined agenda and participation.

(b) **Contingent review**: triggered by an event that significantly alters the external or internal context making a part of the roadmap irrelevant. Leadership should define the focus, agenda, and participation for the specific review.

(c) **KPIs review**: integrated with the periodic or contingent review to assure that dashboards are designed to capture what matters.

(d) **Communication review**: to detect opportunities for improvement in creating stakeholder's perception.

Refine

The roadmap should include a category of activities devoted to learning and improvement, associated with the planning horizons.

Continuous Improvement: This first improvement category in the roadmap achieves small changes in specific roadmap projects, all the time based on simple feedback. Those small changes should be based on the same objectives and the same technology used to define the initial roadmap initiative. These improvements can be executed at the operations level, and are typically limited to H1.

Technology Pivot: This second improvement category in the roadmap may be in response to the perceived or foreseeable evolution of the technological environment and include projects devoted to achieving use case learning and alternate options generation. Those changes should be based on the same objectives, but with alternate technology options. These improvements can be executed at the leadership level, and typically for H1/H2.

New Direction: This third improvement category in the roadmap include projects devoted to new focus, new use cases, a revised technologies portfolio, and/or revised business models and value propositions. Those changes should be based on new objectives, and they may or may not comprise changes in the technology used in relation to the initial roadmap initiative. These improvements are decided by the leadership team or key stakeholders on the recommendation of the leadership and may constitute a significant change to the roadmap. These changes start with a revision of H2/H3, and then trickle down to H1. Sometimes this even calls for change in the leadership team.

A well-tuned review and improvement cycle is a sign of committed leadership, and just as important as a well-defined roadmap. Considering that technology evolution is so rapid and investment capacity for any organization is limited, this step plays a significant role in accomplishing the desired change.

Example: Next Generation NDE Equipment

This is an example to demonstrate how an NDT OEM can build the roadmap to bring Industry 4.0 class NDE equipment using guidance from this book.

Orientation

The Vice President of Engineering happened to attend the basic course on NDE 4.0 at a conference, which built an anxiety to do something as the world appeared to be changing. His conversation with the CEO led to the start of this program. They included VP of engineering and VP of business development to form the 4-member leadership team.

Setup Leadership:

CEO initiates: The leadership team motivated a few managers and engineers to read the books “World of NDE 4.0” and the draft version of an ICDNT roadmap guidance document – a predecessor to this paper, with intent to transform the product portfolio

Purpose defined: Leadership team defined the purpose of their roadmap initiative as **“***Create next generation of NDE systems with digitally enhanced capability and reliability*.”

The objective is to disturb the competitive landscape in their primary market (nuclear, oil, and gas), increase market share in other secondary markets (aerospace and transport), and provide entry to market in at least one additional industry.

External context framed: Extensive list of known and likely aspects were identified, dominated by increasing demand for (a) inspector safety in hazardous environments, (b) rapid data acquisition, and (c) reliable interpretation.

Vision drafted: Based on the purpose and external context, the leadership drafted the vision as “*Autonomous inspections with dependable decision support system*.”

Company policies enhanced: Policies were revised to include managing and securing data as tangible property, ethical considerations around use of AI, employee learning and development for the future, engagement on use of customer owned data, data breach, and business continuity.

Roadmap initiative team identified: The Chief Technology Officer was identified to lead the team with Chief Engineer as deputy. Included in the team were the Director of IT, Director HR, three subject matter experts, and a newly hired programmer. The CEO will continue to be the executive champion.

Internal diffusion: This intent was shared with a select few employees only for the confidential nature of the activity. Those exposed were sworn to secrecy until further notice.

Setup Governance

Internal context identified: Team took a couple of weeks to understand the current state of the company in context of the vision. Gaps in performance capacity and competencies were identified as critical to success. Years of six-sigma had eroded all surplus capacity. Their training was traditionally focused on jobs at hand. The only positive outcome from too much lean is that the company had financial resources to invest. The culture of ethics just needed an expanded awareness around new issues with digital transformation. The team discussed all the normative references for relevance.

External context refined: Another couple of weeks were invested in analyzing the external business environment. Starting with extensive market insight, benchmarking, eco-system mapping, and in-depth PESTEL+I analysis, the team identified one serious political change, one socio-economic shift, one legal concern, and three new external stakeholders with a possibility of one new business model - *servitization* (access to the company's product as an on-demand service).

Prospective context defined: Team held a 2-day workshop to speculate the future based on PESTEL trends and market insights, with an external facilitator, professional at this. It focused on dual transformation – digital and sustainability, with business resiliency as an important consideration. After some deliberation the social responsibility was kept out of scope for the purpose identified.

Several undesirable incidents were identified as possible with two of them likely to occur, needing upfront attention in the roadmap.

This was the most useful exercise during this step of governance setup.

NDE 4.0 Principles accepted: All principles were found to be usable as described, with highest emphasis being on cyber-security, for the need to manage customer data and trust.

Governance guidelines prepared: A new formal document was created to document the above aspects, compatible with the existing operating system. This was reviewed with the leadership team, and marked for annual review, to keep it current.

Code of Ethics revised: It now includes digital aspects, with appreciation that data and algorithms for automation will likely be biased. All the suggested guidelines in this book were acceptable as described.

Digital Transformation Review Board was setup to assure governance and adherence to principles, as documented. This is based on a design review board and materials review board. The new board, which is essentially a subset of the roadmap team, was tasked to draft their expectations.

Create Roadmap

Roadmap initiative kicked off: The team identified roadmap template, held three facilitated ideation sessions to generate data, and established quarterly review cycle. Only one business unit was involved.

Deliberation led to a strategic decision to have 25% of the investment into 2-3 visionary trendsetting projects, 40% for smart forecasting class of development, and 35% at the agile following level. This is unusual, but desirable in this case, given the external context, an opportunity to bring mature digital technologies to the NDE sector, and available financial resources as well as risk capacity.

Scope defined: The primary focus is on digitization of the inspection product and digitalization of NDE processes. This came with an understanding that there will be some digitalization of the manufacturing process along the way. All of this should pave way for total digital transformation later.

Horizons and objectives defined: Horizon-1 objectives included identification and validation of core technologies on existing inspection platforms within 6-18 months. Horizon-2 objectives included autonomous inspection systems and decision assist as separate capabilities within 24-36 months. Horizon-3 objectives included integration of autonomy and intelligence.

Dashboard established: Several suggested KPIs were already in use at this company for business operations. From product standpoint, the additional metrics included autonomy and decision accuracy as outcome indicators and portfolio ROI and digital skills as leading indicators.

All technology options were kept on the table at this point, with intent to build asset digital twins on 'as you go' model.

Roadmap developed: The roadmap is developed using a proprietary tool, with the capability to export as Excel or PowerPoint for external sharing.

Roadmap reviewed and revised: Digital transformation Review Board took a deep dive into the roadmap and did not approve it in the first round. There was poor alignment with several of the NDE 4.0 principles agreed upon upfront.

The roadmap team went back and revised the roadmap to include additional technologies to the planned products. This led to an increase in resource requirements that CEO was not prepared for.

Another round of revisions led to the inclusion of some very creative approaches: (1) Moving some of the newly added technologies to address NDE 4.0 principles into horizon-2 for the subsequent revisions of the product. (2) Adding digitalization to manufacturing process for productivity improvement. (3) Using state government grants for investment in specific manufacturing technologies to offset the cost of productivity improvements. (4) Using supplier financing for introducing their tech into the product. (5) Making advance sales at discounted price to the trusted customer. All this also assumes that initial release of products will generate profits to meet the promises along the supply chain and also fund the subsequent investment. This was an additional financial risk item in the roadmap.

Essentially, the team learned what makes the transformation hard to accomplish and how to address them in a manner of small steps, supported with a serious and solid risk analysis and mitigation plan.

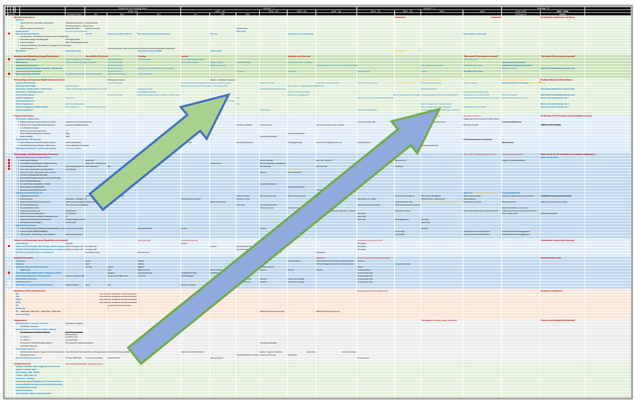
Roadmap validation: Internally, a different set of individuals was tasked to review the details from bottoms-up and top-down view. They identified three assumptions that were high risk. CEO added risk mitigation actions to the roadmap with additional resources.

The trusted customer was engaged for external validation. She had already addressed a few unknowns and refined the priorities during funding conversations.

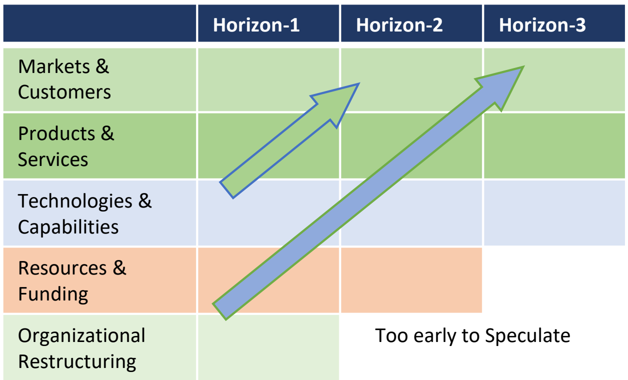
This was a very fruitful exercise. It also alluded to a new role for Digital Products Director in the company.

Roadmap approval: Leadership signed it as approving body. Entire team signed it as show of commitment. It was marked confidential – NEED to KNOW BASIS.

Here is a snapshot of the roadmap that deliberately hides proprietary details.



The graphic here provides a high-level view of the structure, showing meaningful connection from lower left to upper right.



	Horizon-1	Horizon-2	Horizon-3
Markets & Customers			
Products & Services			
Technologies & Capabilities			
Resources & Funding			
Organizational Restructuring		Too early to Speculate	

Prepare Organization

Technology Management process exists in the company. Patrimony protection was added. New roles connected with digital competency were added to the review team for stage gates. Review check lists were enhanced with NDE 4.0 principles and digital ethics checks as per the approved governance guidelines.

General resources estimated. Funding, the biggest one, was estimated based on technology plans, and plausible sources. It forced some reprioritization in favor of low hanging fruit to make the entire program sustainable. Several new suppliers were identified for digital technologies, which also required adding an addition line item in roadmap for supplier qualification. The existing infrastructure was found to be adequate. The biggest gap was in knowledge, particularly the integration piece. The review process was strengthened with additional risk mitigation actions. There is no data set either to try out the AI/ML side of development.

Human talent estimated: This was a bit of a challenge since there is no guidance on the quantification of human talent requirements. This guide only provides a list of skills. An initial swag indicated the need for 3-5 additional engineers with digital and data management skills. It also identified a need for leadership training on the digital side of organizational behavior.

Another major gap identified was in integration skills, since there is no single person who had all three skills - inspection method, diverse applications, and data skills. This firmed up the opinion to create a new role for Digital Products Director. With not enough understanding for such a role in the marketplace, senior leaders created a provisional position description and began the search for a close match. No new certifications were identified at this point.

Leadership demonstrates commitment: Budget was allocated and a weekly cadence for meetings was setup to track progress. These meetings were set up for early in the morning when the CEO is likely to be available in person as well as mentally. A separate room was dedicated to managing operation with visual dashboards/whiteboards.

Transformation

Value management: Since the focus is more on creating autonomous products and not in the automation of manufacturing process, the value creation is embedded in innovation, design, and technologies of the deliverables. The important items addressed in this section are technology management, validation, and qualification, followed by certification and regulatory approvals. The procedures are being revised to include extensive digital context. Each process change will go through single pilot use before formal approval as standard work.

Customer engagement: The trusted customer now plays the role of an advisor and has also offered to be the beta user.

Risk and uncertainty management: Traditional risk matrix is being used considering likelihood, impact, and prevention opportunity to prioritize. Additional rigor was added to the technology reviews at phase-gate process. An external IT form has been engaged for cyber-security aspect of the product and likely a series of cloud-based applications. The business development team is on high alert for early market entrants and value perceptions for such products, so they can be priced fairly.

Financial management: Most systems are in place. The team still needs to figure out data monetization models.

Learning and growth: The team is continuously learning through online courses, and they discuss subjects over weekly lunch-n-learn meetings. They have also identified a set of courses for others to take when it becomes a company-wide initiative. The HR and IT directors have been tasked to continuously refine the processes in place to detect the need for specific skills. This will evolve over the next many months as learning continues.

Learn and improve

This is a new initiative, and the improvement cycles will likely begin in a year or so. The leadership team does understand the need for different levels of analysis and change.

Summary and Outlook

NDE 4.0 is a case of massive transformation. It requires digital technologies to be integrated into the inspection systems, digitalization of workflows, and integration of NDE workflows within value streams. This paper is all about **HOW** to digitalize and digitally transform the NDE system. [1] elaborated **WHY** is it important for almost everyone in the NDE eco-system to embrace it and [3,4] elaborated **WHAT** digital technologies in NDE can help improve design, manufacturing, maintenance, and safety.

Roadmap for digital transformation does have some parallels with traditional roadmaps and transformational efforts, just with the added complexity of uncertainty, major resource investment in technology and talent, and discipline-specific attributes. This paper is guidance document, and every user can adapt to their context, purpose, and limitations.

Fernandez, Hayes, and Gayosso in [12] envision how NDE systems are being disrupted by digital transformation processes as follows: *"In the first NDE lessons often apprentices are still taught the four indispensable elements in a NDE test system (An energy source, a test object, the interaction between that energy source and the test object and a recording medium for this interaction) and while analyzing how the test system does not function in the absence of one or more of those four elements ineludibly a fifth presence, human intervention, often not addressed for its explicit omnipresence which needs to assimilate and capitalize a rising sixth presence, (digital technologies, (including elements such as telepresence, digital aides-de-camp or assisted analysis based in) artificial intelligence, which may be a source of extraordinary opportunities and an unmistakable ally, if properly assimilated, to assist humans to unleash the power of their talent and ingenuity to create and deploy the next generation of NDE systems in the following years"* This transformation has the potential transform for good our discipline and the world.

The NDE 4.0 vision can now become reality with advanced computing and big-data capabilities, using an approach proposed in this guideline paper.

Most importantly, this transformation needs to be viewed as a journey and not a project or a single deliverable goal. It could take a few years depending upon the organizational internal and external context, resources, and commitment to sustainable growth through change. Where does the journey end will not be clear in the beginning, but you will know when you get there. To some, the world of NDE 4.0 appears overwhelming, but a roadmap that breaks down the holistic view into achievable goals, provides a means to successfully take on this journey.

Acknowledgment

The activity regarding the development of this paper was started within the ASNT Committee for NDE 4.0 and finalized within the ICNDT Special Interest Group for NDE 4.0. The authors thank all the supporters of this activity in both organizations.

Specialized NDE 4.0 communities are being formed around professional social networks such as LinkedIn for the diverse palette of NDE professionals or focused in research platforms such as ResearchGate. National NDE organizations such as DGZfP, ASNT or ICNDT have created subcommittees and special interest groups involved actively in establishing NDE 4.0 collaboration, communication, and diffusion platforms and strategies.

Declarations

Funding and/or Conflicts of interests/Competing interests

The authors have no relevant financial or non-financial interests to disclose.

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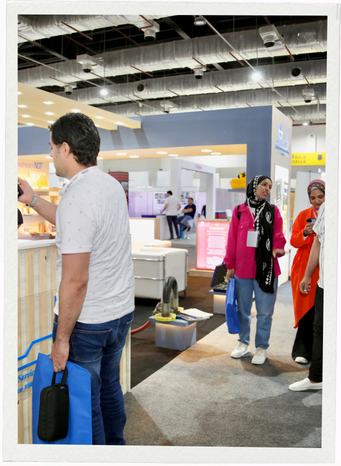


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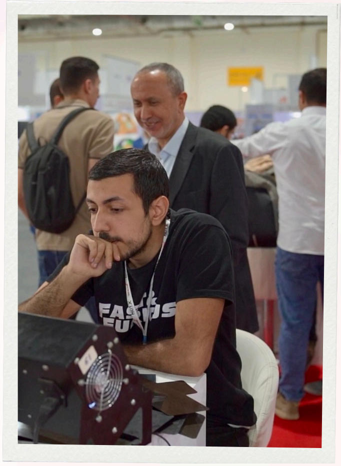

Driving Excellence in Equipment Integrity with cutting edge Technologies: The core of Quality Control and Assurance in Oil & Gas Facilities.

MOHAMMED ABUFOUR
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The oil & gas industry operates in one of the most demanding environments, where equipment reliability and safety are paramount.

As global energy demand continues to grow, maintaining the integrity of infrastructure and assets is more crucial than ever.

Advanced Non-Destructive Testing (NDT) technologies play a pivotal role in ensuring equipment meets rigorous quality and safety standards.

Protecting critical assets like pressure vessels, pipelines, heat exchangers, and storage tanks is essential to prevent failures that could compromise safety, environmental compliance, and profitability.

This article explores how cutting-edge NDT technologies are transforming asset integrity management, addressing inspection challenges, and delivering tangible outcomes for the oil and gas sector.

Driving Excellence in Equipment Integrity.

Oil and gas equipment operates under extreme conditions, exposing equipment to wear, corrosion, and mechanical stress. Ensuring the integrity of critical assets like pressure vessels, pipelines, and storage tanks is essential to avoid safety risks, environmental hazards, and costly downtime.

Equipment integrity is a cornerstone of operational excellence, and failure to maintain it can lead to catastrophic incidents.

To ensure the highest standards of quality, advanced NDT techniques are being employed to detect flaws, predict failures, and validate the fitness-for-service of critical components. By leveraging these technologies, organizations can proactively address potential risks, optimize maintenance schedules, and extend the lifecycle of their assets.

Advanced NDT technologies not only detect flaws and anomalies but also provide the precision and reliability needed to meet the industry's stringent standards. The role of advanced NDT in the oil and gas sector, and the measures required to optimize Oil and Gas Facilities equipment inspection using cutting-edge NDT technologies.

To meet the highest standards, advanced NDT techniques are employed to detect flaws, predict failures, and validate the fitness-for-service of critical components. These technologies enable proactive risk mitigation, optimize maintenance schedules, and extend asset lifespans.

Techniques such as Phased Array Ultrasonic Testing (PAUT), Time-of-Flight Diffraction (TOFD), and Eddy Current Testing (ECT) are at the forefront of these efforts, providing accurate, real-time assessments that enhance safety and operational efficiency.

Achieving excellence in equipment integrity requires more than advanced tools; it *demands a systematic approach* that integrates technology, expertise, and process efficiency.

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Reliability & Asset Integrity

Harsh operating conditions in the oil and gas sector—such as extreme temperatures, high pressures, and corrosive environments—make asset integrity management challenging.

A comprehensive strategy to identifying, assess, and mitigating risks across an asset's lifecycle is essential.

Reliability is a *key factor in asset integrity management, directly affecting operational efficiency and profitability.* Advanced NDT technologies enhance reliability by providing precise insights into equipment condition, enabling predictive maintenance strategies.

Detecting early signs of wear, corrosion, and cracking, advanced NDT minimizes unplanned outages, reduces repair costs, and extends infrastructure lifespan.

Advanced NDT technologies also offer non-invasive inspection methods, allowing operators to evaluate assets like pipelines, pressure vessels, and offshore platforms without disrupting operations. These technologies help ensure compliance with safety regulations while maintaining operational efficiency.

Inspection Challenges and the Role of Advanced NDT Professionals.

Inspection in the oil and gas industry often faces challenges such as limited accessibility, complex geometries, and environmental constraints. Advanced NDT engineers and technicians play a critical role in overcoming these hurdles by employing innovative techniques and technologies to deliver reliable results.

By using Advanced NDT Technologies like drones with ultrasonic sensors, robotic crawlers for confined spaces, and remote monitoring systems enable professionals to access hard-to-reach areas efficiently. Their expertise in interpreting data and identifying critical defects ensures timely issue resolution, preventing costly failures.

To optimize performance, NDT professionals require deep knowledge of material science, flaw characterization, and signal analysis. Continuous training, certification, and professional development are essential for keeping pace with technological advancements and industry standards.

What is Quality Assurance?

Quality assurance (QA) is a systematic approach to ensuring that products, processes, and services meet defined standards of quality, reliability, and safety. In refinery plant operations, QA involves thorough inspections, testing, and monitoring to confirm that assets perform as intended and comply with regulatory and operational requirements.

QA is proactive and focuses on defect prevention through rigorous planning, implementation of best practices, and verification of compliance. It encompasses various activities, including:

- Establishing inspection protocols.
- Ensuring the competency of personnel.
- Validating testing methods.
- Documenting and analyzing inspection results.

Effective QA focuses on defect prevention through rigorous planning, best practices, and verification of compliance. Key activities include:

- **Competence of Personnel**: Certifying inspectors (e.g., ASNT NDT Level III) and providing ongoing training in advanced technologies.
- **Standardized Procedures**: Developing and adhering to NDT procedures aligned with industry standards.
- **Equipment Calibration and Maintenance**: Calibrating NDT equipment regularly to maintain accuracy and ensure optimal performance.
- **Data Management and Analysis**: Implementing robust systems for recording, storing, and analyzing inspection data.
- **Continuous Improvement**: Conducting periodic audits and integrating feedback to improve future inspections.

Optimizing QA through Advanced NDT Technologies

Advanced NDT technologies are redefining how the oil and gas industry approaches asset integrity. By integrating these methods into QA protocols, facilities can enhance reliability, reduce downtime, and optimize maintenance strategies.

Technologies such as Phased Array Ultrasonic Testing (PAUT), Time-of-Flight Diffraction (TOFD), and Digital Radiography (DR) enable precise flaw detection, even in challenging environments. Their benefits include:

- **Predictive Maintenance**: Anticipate failures and plan maintenance proactively.
- **Minimized Downtime**: Conduct in-service inspections without halting operations.
- **Early Defect Detection**: Identify issues like corrosion and cracking before escalation.
- **Enhanced Safety**: Mitigate catastrophic failures by detecting critical flaws early.
- **Cost Efficiency**: Reduce repair costs and streamline inspections.
- **Regulatory Compliance**: Meet industry standards such as API, ASME, and ISO.

By integrating advanced NDT technologies, operators achieve higher inspection reliability and asset integrity management standards.

Role of Advanced NDT Technologies to Enhance Asset Integrity Quality

Traditional inspection techniques, while valuable, often have limitations in detecting subsurface defects, complex geometries, or defects in challenging environments.

Advanced NDT technologies overcome these limitations by providing more accurate, efficient, and non-intrusive evaluation.

These technologies not only enhance the quality of inspections but also support decision-making processes by providing actionable insights into asset health.

These techniques provide unparalleled accuracy and efficiency, enabling the detection of minute defects that traditional techniques might miss.

Asset integrity quality is a cornerstone of refinery plant operations.

Advanced NDT technologies play a pivotal role in enhancing this quality by:

- **Enabling Predictive Maintenance**: By integrating NDT data with predictive analytics, operators can anticipate failures and schedule maintenance proactively.

- **Minimizing Downtime**: Advanced methods allow for in-service inspections, reducing the need for equipment shutdowns.

- **Detecting Early-Stage Defects**: Techniques like Phased Array Ultrasonic Testing (PAUT) and Time-of-Flight Diffraction (TOFD) can identify flaws before they escalate.

- **Enhancing Safety**: Reliable and early defect detection minimizes the risk of catastrophic failures, failures, protecting both personnel and infrastructure.

- **Improving Cost Efficiency**: Preventive maintenance based on accurate NDT results reduces repair and replacement costs. Faster and more accurate inspections streamline operations.

- **Ensuring Regulatory Compliance**: Advanced NDT helps operators adhere to industry standards such as API, ASME, and ISO and safety regulations.

- **Cost Savings**: Proactive maintenance reduces repair costs and unplanned downtime.

- **Sustainability**: By extending asset lifespans, these technologies contribute to more sustainable operations.

Advanced NDT technologies directly contribute to achieving QA objectives by enhancing inspection effectiveness and efficiency. *Below are some examples of how these technologies support QA:*

- **Phased Array Ultrasonic Testing (PAUT)**: Provides high-resolution imaging of welds and components, allowing for precise flaw sizing and characterization.
- **Time-of-Flight Diffraction (TOFD)**: Provides high-resolution data for critical weld inspections, detects and sizes critical cracks in pressure vessels and pipelines with unparalleled precision.
- **Remote Visual Inspection (RVI)**: Uses drones and robotic systems to inspect confined spaces, reducing risks and improving safety.
- **Magnetic Flux Leakage (MFL) Tank Inspection**: Ideal for detecting corrosion and pitting in storage tanks bottom plates.
- **Digital Radiography (DR)**: Delivers real-time imaging with enhanced clarity, ensuring timely decision-making and reduced exposure times.
- **Acoustic Emission Testing (AET)**: Monitors structural integrity during operation, detecting active defects such as cracking and corrosion enable continuous monitoring of equipment under operational conditions.
- **Guided Wave Testing (GWT)**: offer insights into the condition of assets/pipeline, including hard-to-reach areas.
- **Electromagnetic Testing (ET)**: Detects surface and subsurface defects in non-ferrous materials, ensuring comprehensive coverage.

> By integrating these technologies into QA frameworks, operators can achieve a higher standard of inspection reliability and asset integrity management.

In Summary

The oil & gas industry must prioritize operational excellence, safety, and sustainability. Advanced NDT technologies are transforming QA practices by providing accurate, efficient, and reliable inspection solutions. These technologies address traditional limitations methods, enable proactive maintenance, and ensure compliance with stringent industry standards.

The true value of these technologies lies in the hands of skilled professionals whose expertise turns data into actionable insights. By investing in cutting-edge technologies and continuous professional development, the industry can achieve unparalleled quality, safety, and operational excellence.

In an era where operational ***excellence*** *is essential, embracing advanced NDT technologies is no-longer optional _ it is a necessity for ensuring safety, efficiency, and sustainability.*

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Hidden Challenges in NDT
Technical and non-technical

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INTRODUCTION

Non-Destructive Testing (NDT) is a cornerstone of quality assurance and safety across industries, including aerospace, manufacturing, civil engineering, and energy. This indispensable discipline involves the inspection, testing, and evaluation of materials, components, and structures without causing damage. Its importance cannot be overstated NDT ensures the integrity of critical infrastructure, prevents catastrophic failures, and saves lives. However, as the industry evolves, especially with the advent of *NDE 4.0 (the fourth industrial revolution in NDT)*, it faces a myriad of hidden challenges—both technical and non-technical—that need to be addressed to unlock its full potential.

The Evolution of NDT: From NDE 1.0 to NDE 4.0

To fully appreciate the challenges in NDT, it's essential to understand its evolution. The journey from NDE 1.0 to NDE 4.0 represents the industry's progressive adaptation to technological advancements and changing industrial requirements.

NDE 1.0: Manual Inspection and Visual Testing.

In the late 19th and early 20th centuries, NDT primarily relied on manual inspection and visual testing. Human inspectors examined materials and structures visually to detect defects. This method was straightforward but subjective, time-consuming, and prone to human error.

NDE 2.0: Emergence of Specialized Techniques

By the mid-20th century, specialized techniques like magnetic particle testing, dye penetrant testing, and ultrasonic testing were introduced. These methods enabled more accurate and reliable detection of surface and subsurface defects, significantly expanding the scope of NDT applications.

NDE 3.0: Digitalization and Automation

The late 20th and early 21st centuries saw the integration of digital technologies into NDT. Techniques such as digital radiography, phased array ultrasonic testing, and time-of-flight diffraction (TOFD) revolutionized the field. Automation began to reduce human intervention, improving efficiency and consistency.

NDE 4.0: Integration of Advanced Technologies

Today, NDT is entering the era of NDE 4.0, characterized by the integration of cutting-edge technologies like Artificial Intelligence (AI), the Internet of Things (IoT), Augmented Reality (AR), Virtual Reality (VR), and Machine Learning (ML). While these advancements promise smarter, faster, and more data-driven NDT processes, they also introduce new challenges, particularly in implementation, workforce readiness, and collaboration across the industry.

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Technical Challenges in NDT

1. Data Volume, Quality, and Accuracy

The sheer volume of data generated by NDE 4.0 technologies presents challenges in storage, processing, and analysis.

- **Data Overload**: Advanced systems such as phased array ultrasonic testing and IoT-enabled sensors produce enormous amounts of data, overwhelming traditional storage and processing infrastructures.
- **Data Quality**: Ensuring data accuracy and reliability is critical. Poor-quality data can lead to incorrect conclusions, jeopardizing safety and quality.
- **Data Integration**: Integrating data from multiple sources, including imaging systems and historical records, requires sophisticated algorithms and software. Variations in data formats and standards further complicate the process.

The industry must invest in robust data management systems, advanced analytics tools, and standardized protocols to handle these issues effectively.

2. Cybersecurity and Privacy Concerns

As NDT systems increasingly rely on connected technologies, they become vulnerable to cyberattacks.

- **Data Breaches**: Sensitive inspection data, such as defect reports, could be targeted by hackers.
- **System Vulnerabilities**: IoT-enabled sensors and remote monitoring systems are potential entry points for attacks.
- **Privacy Issues:** The collection of inspection data raises concerns about compliance with data protection regulations.

The industry must adopt strong cybersecurity measures, including encryption, secure communication protocols, and regular audits, while collaborating with cybersecurity experts.

3. Sensor Reliability and Calibration

Sensors are the backbone of advanced NDT systems, but ensuring their reliability presents several challenges:

- **Sensor Drift**: Over time, sensors lose accuracy due to environmental factors or calibration errors.
- **Environmental Interference**: Harsh conditions, such as extreme temperatures, can degrade sensor performance.
- **Calibration**: Regular calibration is essential but resource-intensive, especially for large-scale operations.

Developing durable, self-calibrating sensors and real-time monitoring systems can help address these challenges.

4. Standardization and Certification

The rapid adoption of NDE 4.0 technologies has outpaced the development of industry standards and certification processes.

- **Inconsistent Practices:** Without standardized protocols, organizations may use varying methods, leading to inconsistencies.
- **Certification Gaps:** Current certification programs often lack coverage for emerging technologies like AI and IoT.
- **Regulatory Delays**: Regulators may struggle to keep up with innovations, delaying implementation.

Close collaboration with standards organizations and the development of updated guidelines and training programs are vital.

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5. Interoperability and System Integration

Integrating diverse technologies such as AI, IoT, and AR into a cohesive system is challenging.

- **Compatibility Issues:** Proprietary software and hardware hinder seamless integration.
- **Data Silos:** Non-interoperable systems limit comprehensive data analysis.
- **System Complexity**: The complexity of integrated systems demands specialized expertise.

Developing open standards and modular, scalable systems will simplify integration and enhance interoperability.

6. Cost and Return on Investment (ROI)

The adoption of NDE 4.0 technologies involves substantial financial investment.

- **Initial Costs**: Advanced equipment and software are expensive.
- **Maintenance:** Ongoing expenses for updates and calibrations add to the cost.
- **ROI Uncertainty:** Benefits may take time to materialize, complicating cost justification.

Organizations must evaluate ROI carefully and explore cost-sharing models such as partnerships or leasing.

7. AI and Machine Learning Algorithms

AI and ML are central to NDE 4.0, but their maturity levels pose challenges.

- **Algorithm Bias:** AI algorithms trained on biased data produce unreliable results.
- **Complex Defects**: Rare or intricate defects may be beyond AI's current capabilities.
- **Continuous Learning**: AI systems require ongoing updates, which can be resource intensive.

Investing in high-quality training data and robust algorithms while combining AI with human expertise can mitigate these issues.

8. Real-World Variability and Adaptability

NDT must operate reliably in diverse environments.

- **Environmental Factors:** Harsh conditions can impair system performance.
- **Material Variability**: Different materials require tailored inspection methods.
- **Operational Constraints**: Time & resource limitations in field inspections pose challenges.

Developing ruggedized technologies and conducting extensive field testing will ensure reliability across conditions.

Non-Technical Challenges in NDT

While technical challenges like data management, cybersecurity, and sensor reliability in NDE 4.0 receive significant attention, non-technical challenges often remain overlooked. Rooted in human and organizational dynamics, these challenges can profoundly hinder progress if left unaddressed. This article explores some of these hidden yet critical obstacles and their implications for the future of Non-Destructive Testing (NDT).

1. Limited Knowledge of Multiple NDT Methods

Many NDT professionals are certified in only one or two methods, such as Ultrasonic Testing (UT) or Radiographic Testing (RT). While specialization has its merits, this limited scope can lead to gaps in defect detection and decision-making. For instance, a linear defect in a weld may be easily identifiable through UT but could go undetected in RT or Magnetic Particle Testing (MT). This lack of cross-method expertise risks compromising safety and accuracy. Expanding professionals' knowledge across multiple NDT techniques is crucial to making informed and reliable assessments in diverse scenarios.

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2. Lack of Awareness Among Non-NDT Stakeholders.

NDT often exists as a niche field, underappreciated by senior management and other non-NDT stakeholders in industries that depend on it. This limited awareness can lead to misconceptions about the role of NDT teams, often viewing them as bottlenecks to production rather than as essential contributors to safety and quality.

Bridging this gap requires targeted outreach to non-technical audiences. Leveraging engaging content such as videos, articles, and social media campaigns can help raise awareness about the critical role NDT plays in maintaining operational integrity and safety.

3. Generic Training Lacking Industry-Specific Focus

NDT methods and applications differ significantly across industries. For instance, the oil and gas sector employ techniques that vary from those used in aerospace or civil engineering. Despite these distinctions, most training programs are generic, offering broad overviews rather than sector-specific insights.
To meet the demands of NDE 4.0, training programs must evolve. Industry-specific modules and centralized training hubs, where experts from diverse fields share their experiences, could better prepare technicians for the unique challenges of their respective industries.

4. Manpower Competency

Even with technological advancements, the competency of NDT personnel remains a cornerstone of reliable results. In methods like manual ultrasonic testing (MUT), the technician's judgment often serves as the final authority. However, without robust cross-check mechanisms, human errors may go unnoticed, potentially leading to significant consequences. Certification alone is insufficient; competency must be validated through rigorous practical exams and ongoing evaluations to ensure technicians maintain high levels of expertise and reliability.

5. Training for High-Stress Situations

NDT professionals frequently operate in high-pressure environments, where their decisions can have far-reaching consequences. For example, rejecting a batch of components could delay production schedules, while approving defective parts could lead to catastrophic failures. Technical training alone is inadequate to prepare professionals for such scenarios. Incorporating mental resilience and stress management into NDT training programs can improve decision-making under pressure and promote the well-being of technicians.

6. Lack of a Centralized Platform for Collaboration

The NDT industry lacks a unified platform where professionals can report violations, share experiences, and access valuable data on defects and accidents. Such a platform could foster collaboration, enable knowledge sharing, and provide a forum for discussing challenges and innovations.
Industry leaders and organizations should spearhead the development of this platform, empowering professionals to collectively address issues and advance the field.

7. Non-Experts Conducting NDT Audits and Approvals

In many industries, audits and approvals related to NDT are conducted by agencies or personnel without specialized NDT knowledge. This lack of expertise can result in oversights that compromise the quality and effectiveness of inspections.
To enhance reliability, NDT-specific audits should be performed by qualified professionals who understand the nuances and limitations of various testing methods.

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8. Bridging the Gap for Seasoned Professionals

Many experienced NDT professionals started their careers before the advent of advanced technologies like Artificial Intelligence (AI) and the Internet of Things (IoT). This can make it challenging for them to adapt to the digital tools and systems integral to NDE 4.0. Tailored training programs that respect their expertise while introducing new technologies can bridge this gap, blending traditional knowledge with modern capabilities to achieve a balanced approach.

9. Undervaluing Experience in NDT

Although industry standards often mandate that NDT processes be supervised by Level III certified professionals, little distinction is made between newly certified personnel and those with decades of experience. To reduce costs, some organizations opt for less experienced professionals, potentially compromising quality and safety.
Recognizing and leveraging the expertise of seasoned professionals is vital. Their insights and problem-solving skills are irreplaceable and should be valued to uphold high standards in NDT practices.

10. Disconnect Between Researchers and Field Technicians

The NDT community is often divided into researchers who develop advanced techniques and field technicians who apply them. This disconnect can hinder progress, as researchers may lack awareness of real-world challenges, while field technicians may not have access to the latest innovations. Enhanced collaboration and communication between these groups are essential.
Researchers should focus on addressing practical problems, and field technicians should be empowered with tools and knowledge to integrate cutting-edge technologies into their workflows.

CONCLUSION

Navigating the Path to NDE 4.0

The transition to NDE 4.0 represents a transformative era for NDT, blending advanced technology with the industry's foundational principles of safety and quality. Addressing both technical and non-technical challenges requires a balanced, holistic approach.

Robust data management, advanced cybersecurity, and durable technologies must be paired with workforce training, collaboration, and awareness initiatives.

By tackling these challenges, the NDT industry can unlock the full potential of NDE 4.0, ensuring a safer, more efficient, and innovative future. Collaboration, continuous improvement, and a commitment to excellence will guide the way forward, reinforcing NDT's critical role across industries.

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LOCAL POST WELD Heat Treatment for Pressure Vessels & Case history

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Post Weld Heat Treatment (PWHT) is a controlled heat treatment process performed after welding under certain conditions to produce certain desirable changes in its properties. Its primary objectives are tempering, relaxation of residual stress, reduce hardness and hydrogen removal.

Weld residual stresses are the result of internal forces occurring without any external forces when the heating of the weld area relative to the adjacent material experiences restrained thermal expansion. Tensile residual stresses are induced in areas near the weld deposit due to the restraint of the adjacent (colder) base metal.

These residual stresses increase the likelihood for crack initiation and propagation and depending on the process conditions and service environment, may increase the risk of stress corrosion cracking, fatigue cracking, and ultimately brittle fracture.

Most PWHT governing codes recommend that a work piece undergo PWHT in a furnace to ensure that all weldments are uniformly heated to avoid thermally induced stresses. However, codes allow for local PWHT where a local section of a much larger work piece, such as a pressure vessel, is allowed to be heated locally, provided that harmful temperature gradients are avoided.

Key Regions in Local PWHT

The ***three main regions*** utilized in the local PWHT are defined below and illustrated in figure 1 [1]

Soak Band (SB): through-thickness volume of metal that is required to be heated to within the post weld heat treatment temperature range. As a minimum, it shall consist of the weld metal, the HAZ, and a portion of the base metal adjacent to and on each side of the weld being heated.

Heated Band (HB): surface area over which the heat is applied to achieve the required temperature in the soak band. The heated band consists of the soak band width on the outside surface of the component, plus any adjacent base metal necessary to both control the temperature and achieve an acceptable temperature on the inside of the pipe or tube.

Gradient Control Band (GCB): surface area over which insulation or supplementary heat source, or both, may be placed. The gradient control band encompasses the soak band, the heated band, and sufficient adjacent base metal to ensure that harmful temperature gradients are not generated within the heated band.

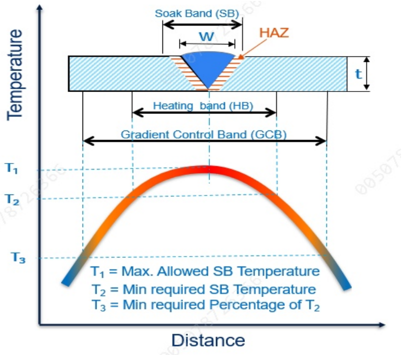

Figure-1: Definition of Terms for Local Circumferential Band Heating of Weld.

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Variability in Local PWHT Standards

Despite general agreement on the principles of local PWHT, significant variations exist across different codes regarding SB, HB, GCB sizing, and holding time/temperature. This can be recognized by comparing the PWHT requirements between different sections of ASME BPVC and ASME B31 piping codes.

If the HB and GCB are not properly calculated and applied, it can lead to inefficient release the residual stresses or possibly distortion of the heated part. The high residual stresses increase the probability of in-service cracking especially for services subjected to environmental cracking (eg. Caustic SCC). In some cases, the application of Finite Elements Analysis (FEA) is required due to the geometrical limitations of the part or the presence of the structural discontinuity in the vicinity of the weld. Figure-2 shows a case of distortion in a vertical vessel resulted from improper application of local PWHT [2].

Figure-2 Distortion in a vertical vessel resulted from improper application of local PWHT [2]

Service Requirements

In certain service environments, failure mechanisms such as alkaline stress corrosion cracking (ASCC) or hydrogen stress cracking (HSC) may be operative. These failure mechanisms can be driven by factors such as residual tensile stress and/or hardened microstructure. As a result, exemption from PWHT based upon thickness is not relevant when such environments are present. Codes generally do not recognize the service environment. Hardness is sometimes used as an index of susceptibility to stress corrosion in certain environments.

When the objective of PWHT is to achieve specific hardness requirements, it is important to recognize that fabrication code minimum temperatures may not be adequate. An example for that is the recommended hold temperature for PWHT in amine and caustic cracking service to be 635 ±15°C (1175 ±25 °F) [13] against 595 °C (1100 °F) in ASME BPVC Sec VIII div.1 for P No.1 materials. Figure-3 Provides graphical representation for Interrelation of the various cracking mechanisms.

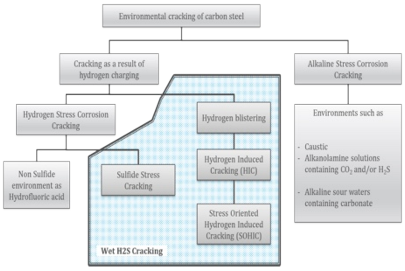

Figure-3 Interrelation of the various cracking mechanisms [13]

Residual Stresses

Welding involves the deposition of molten metal between two essentially cold parent metal faces. As the joint cools the weld metal contracts but is restrained by the cold metal on either side; the residual stress in the joint therefore increases as the temperature falls. The magnitude of these residual stresses can be as high as the yield strength of the weld metal.

To reduce this high level of residual stress, the component is reheated to a sufficiently high temperature. As the temperature is increased the proof strength falls, allowing deformation to occur and residual stress to decrease until an acceptable level is reached. Figure-5 shows change in yield (proof strength) of three common materials.

It is important to note that the threshold residual stress levels in such cases are often less than those required for brittle fracture related concerns, and more detailed requirements may therefore apply. [4]

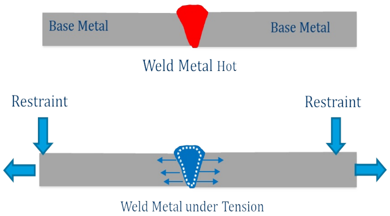

Figure-4 Tensile residual stress during cooling of weld metal

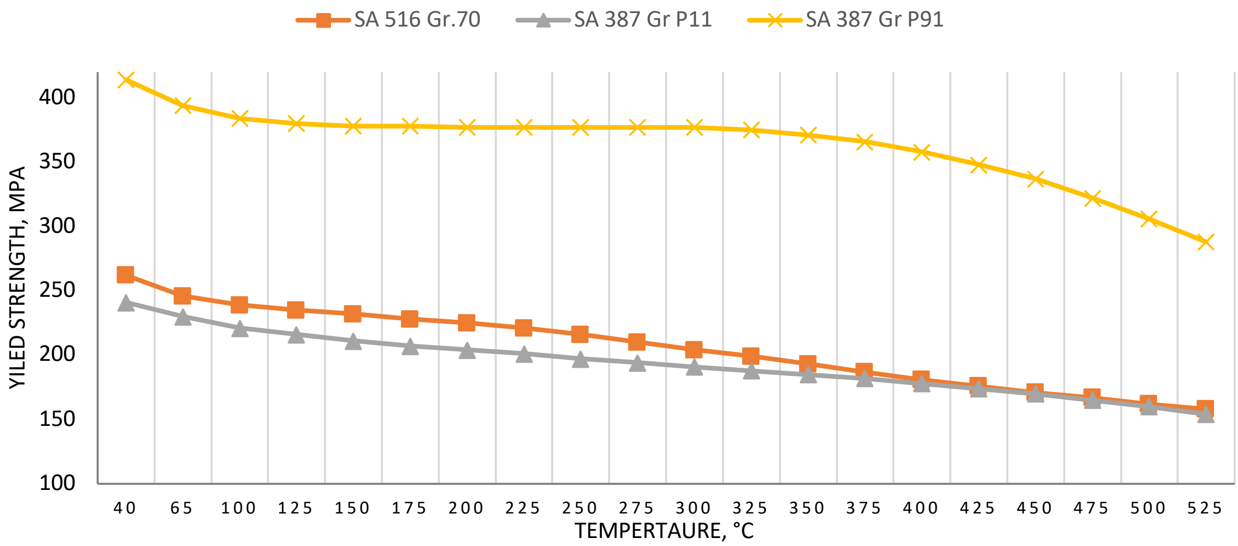

Figure-5 Comparison of yield strength of SA516 Gr. 70, SA387 Gr. P11 and SA387 P91[12]

(SB, HB, GCB) between different codes. While residual stresses can be reduced by application of a PWHT, this option is not always available in the case of Corrosion Resistant Alloys (CRAs). Other methods of controlling residual stresses are the use of alternating or specific weld directions to minimize distortion as well as successive weld layers tempering back the underlying weld.

Design of grooves to reduce weld metal volume, preheating of weld, and assembly procedures with proper restraints can all aid in reducing distortion. [10]

There are differences in the guidelines for the PWHT application between different codes; Table-1 provides comparison between different codes for the requirements of local PWHT bands.

Table-1: Comparison between different codes requirements

Code	SB Size	HB Size	GCB Size
ASME BPVC sec VIII div.1 and 2	t or 2in (50 mm) whichever is less on either side of weld	Temperature gradient is not harmful (no specific guidelines)	Temperature gradient is not harmful (no specific guidelines)
ASME BPVC Sec I	t or 2in (50 mm) whichever is less on either side of weld(1)	Controlled temperature to prevent harmful gradient (no specific guidelines) (1)	Controlled temperature to prevent harmful gradient (no specific guidelines) (1)
ASMP B31P	3t(1)	No specific guidelines (1)	No specific guidelines (1)
WRC 452 and AWS D10.10	Follow ASME BPVC SEC VIII	SB+$2\sqrt{R\,t}$ on either side of the weld (3)	HB+$2\sqrt{R\,t}$ on either side of the weld(3)
PD 5500 and AS 1210 (2)	Weld + HAZ	$5\sqrt{R\,t}$ Centered at the weld (3)	$10\sqrt{R\,t}$ Centered at the weld(3)

Notes:
(1) ASME BPVC Sec I and ASME B31P includes separate appendixes for materials under P no. 15E (e.g. P91 grade)
(2) PD 5500 and AS 1210 referenced from WRC 452.
(3) R is the inside radius, and t is the nominal thickness.

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Impact on Notch Toughness

In certain cases, PWHT may introduce reheat cracking and/or a reduction in notch toughness [7]. the effect of PWHT on notch toughness of weld metals varies widely according to material composition, strength level, flux, heat input, and the target temperature and hold time of PWHT.

Starting from edition 2014 of ASME B31.3, PWHT is no longer a mandatory requirement for any wall thickness provided that multi-pass welding is employed, and a minimum preheat is applied at 95 °C (200 °F) for thicknesses greater than 25 mm (1 inch).

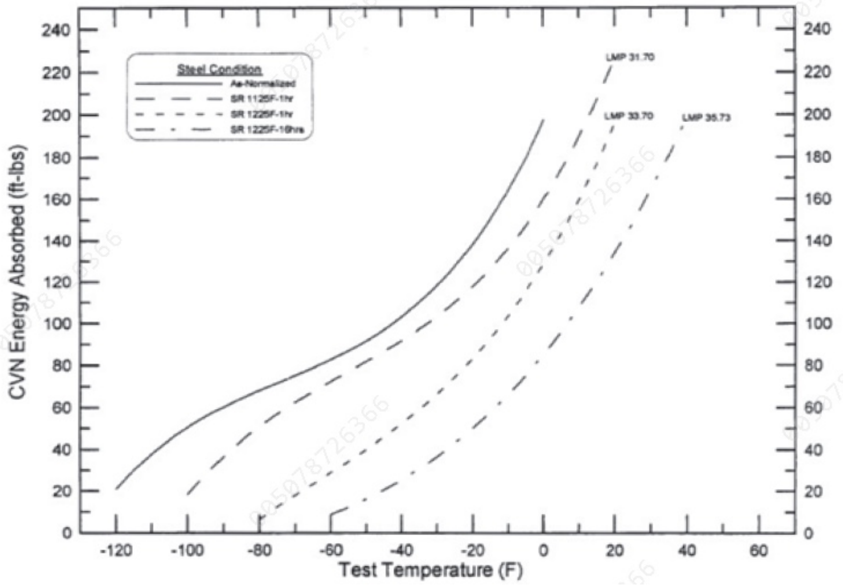

Figure 6: The Effect of PWHT on CVN Energy for SA-516-70 as a Function of Temperature for Different Stress Relief Conditions [11]

Special Consideration for P91 materials and Creep-Strength Enhanced Ferritic (CSEF) Steels

The 9Cr-1Mo-V steel, designated as P91, is a martensitic-type low carbon steel that exhibits enhanced creep and creep-rupture properties that are achieved by a combination of alloy composition and heat treatment. These steels are referenced in Section IX of the ASME Code as creep-strength enhanced ferritic (CSEF) [22]. Specifically developed for service at temperatures where design stresses are limited by the creep and creep-rupture strengths, this steel exhibits poor notch toughness and susceptibility to stress corrosion cracking in the as-welded condition. In addition, the metallurgical characteristics require careful control of welding parameters to minimize hydrogen induced cracking. P91 is only one example of steels that are part of the CSEF steels being promoted for service in the creep range. [7]

CSEF steels including grade P91 has special considerations for the application of PWHT as captured separately in EPRI publications, ASME Sec. I mandatory appendix VIII and ASME B31P non-mandatory appendix B and ASME B31P.

Table-2: Comparison between different codes requirements for CSEF P no. 15E materials

Code	SB Size	HB Size	GCB Size
ASME BPVC sec VIII div.1(1)	t or 2in (50 mm) whichever is less on either side of weld	Temperature gradient is not harmful (no specific guidelines)	Temperature gradient is not harmful (no specific guidelines)
ASME BPVC Sec I Mandatory appendix VIII	- 1.5 t In each side of weld for NPS <= 4in - 6 t In each side of weld for NPS <= 4in - 10 t on each side of weld for NPS > NPS 8 in	SB + on each side	HB + 4t on each side
ASMP B31P	- 1.5 t in each side of weld for NPS <= 4in - 6 t In each side of weld for NPS <= 4in - 10 t on each side of weld for NPS > NPS 8 in	No specific guidelines (1)	No specific guidelines (1)
WRC 452 and AWS D10.10	Follow ASME BPVC SEC VIII	SB+$2\sqrt{R\,t}$ on either side of the weld	HB+$2\sqrt{R\,t}$ on either side of the weld
PD 5500 and AS 1210 (1)	Weld + HAZ	$5\sqrt{R\,t}$ Centered at the weld	$10\sqrt{R\,t}$ Centered at the weld

Notes:
(1) No special size for P no. 15E materials

In addition to the special sizing of SB, HB and CGB provided in ASME BPVC sec I and ASME B31P for P nio.15 E materials, the codes provide special considerations of the composition of the filler metal used in welding. In note (3) of table UCS-56-11 in ASME BPVC sec VIII dvi.1 the percent of Ni + Mn in the filler metal limits the PWHT holding temperature for percent less than 1.0 %, PWHT temperature shall be 790°C and for percent between 1.0 and 1.2, PWHT shall be 780°C and for higher than 1.2%, PWHT temperature shall be 10 °C lower than the lower critical transformation temperature. Similar requirements listed in notes of table PW-39-5 in ASME BPVC Sec I

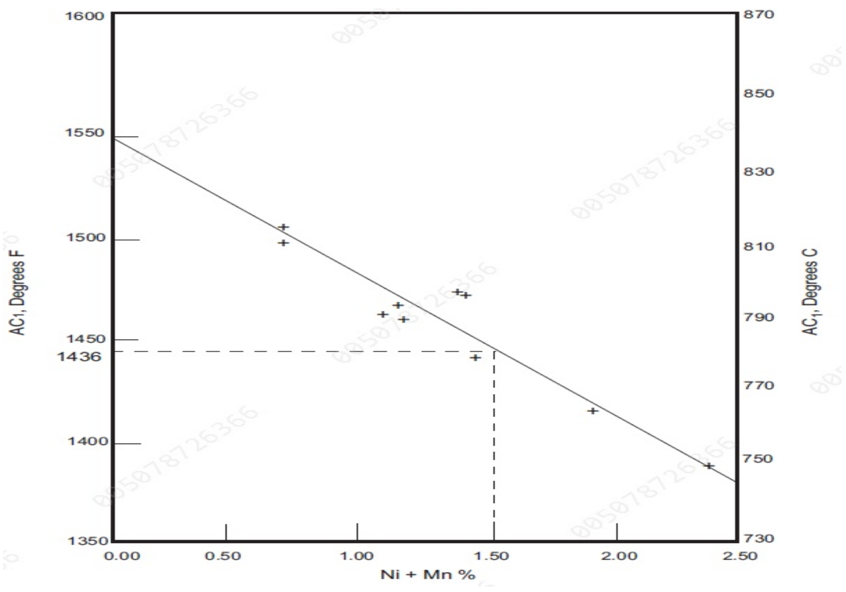

Figure-7: Effect of Ni + Mn on AC1 of P91 weld metal

In Para 131.6 in ASME B31.1, it required to cool the P no. 15E materials below the approximate martensite finish temperature (Mf) before application of PWHT providing the approximate Mf is 190°C for filler material having Ni _ Mn <=1.2 % and 95°C for filler metal having Ni + Mn > 1.2 %. Notice the major impact of the filler wire composition.

An important note in table UCS-56-11, PWHT for P-No.15E materials in ASME BPVC Sec VIII div.1 (note (3) (c)(2)) limited the maximum operating temperature for any vessel constructed using filler metal with Ni + Mn in the excess of 1.2% to maximum 525°C (975°C). Suh comment can be overlooked by designer or manufacturer of the vessel.

The quantity of Ni + Mn affects the Ac1 as shown in Figure 7. In order that PWHT temperature does not exceed the lower critical temperature Ac1, Ni + Mn content is typically limited to provide safeguard against austenite reformation during PWHT. [14]

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CALCULATED EXAMPLE,

assuming steam pipe at outlet of a boiler fabricated from P91 material with size NPS 20 in and 30mm thickness and below the required SB, HB and GCB by different codes and standards as listed in table-3 and figure-8

Table-3: Working example for P91 pipe, NPS 20 in and thickness 30 mm

Code	SB, mm	HB, mm	GCB, mm
AWS D10.10 / WRC 452	90 (1)	418	746
ASME sec VIII div.1	120(1)	Not specified	Not specified
ASME P31P appendix B	300	350	590
ASME BPVC sec I Appendix VIII	600	840	1080

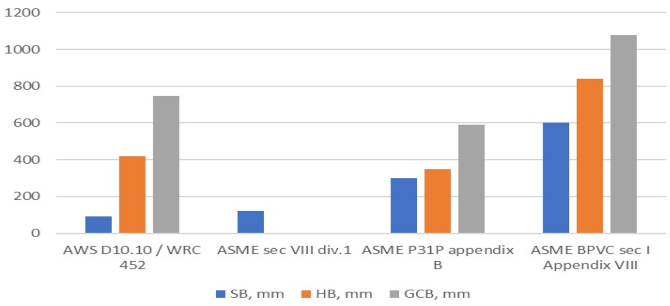
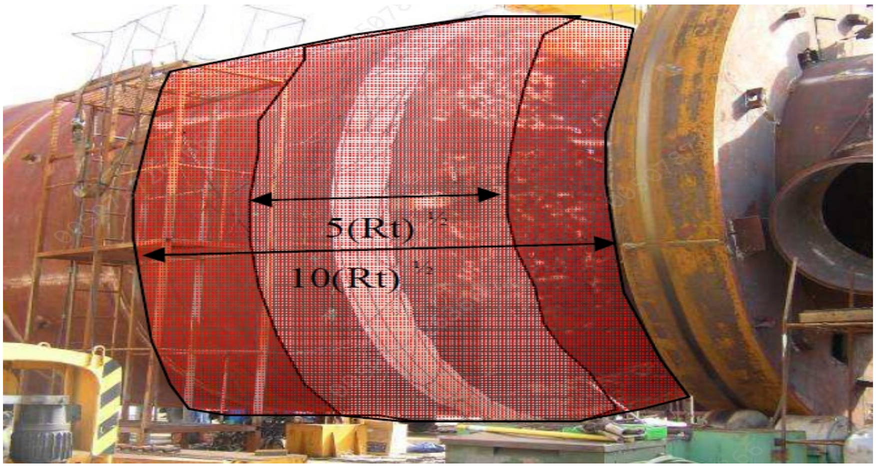


Figure-8: Working example for P91 pipe, NPS 20 in and thickness 30 mm

From the example results, notice the big differences between the requirements for different codes for this specific material

CASE HISTORY

The photo in figure-9 is for a 90 mm thickness P11 (1.25 Cr- 0.5 Mo) vessel TAKEN during the fabrication local PWHT process of the closure weld. The white band is the insulation applied (GCB) which covers only the soak band while the other imaginary dark red band is the extent of the GCB as it should be per the requirements of BS5500 as identified in WRC 452. That was a result of the misinterpretation and misunderstanding of the local PWHT requirements, especially the design code of the vessel (ASME BPVC sec VIII div.1) do not specify the HB or the GCB size. This weld cracked after few years of operations due to the improper application of the PWHT. [15]



CONCLUSION

Local PWHT is a highly effective stress-relief technique when applied correctly, but its success hinges on precise adherence to code-specific requirements and metallurgical principles. Differences in PWHT criteria across standards necessitate a thorough evaluation to optimize treatment parameters for each application. In critical applications, advanced techniques like FEA can provide valuable insights into optimizing PWHT execution to prevent failures and ensure long-term component integrity.

REFERENCES:

[1] Standard Heat Treatments for Piping, ASME B31P-2023

[2] Establishing Recommended Guidance for Local Post Weld Heat Treatment Configurations Based on Thermal-Mechanical Finite Element Analysis, E2G

[3] Recommended Practices for Local Heating of Welds in Pressure Vessels, WRC 452

[4] Recommended Practices for Local Heating of Welds in Piping and Tubing, AWS D10.10

[5] ASME BPVC Sec VIII div.1

[6] ASME BPVC Sec I

[7] Degradation of Notch Toughness by a Post Weld Heat Treatment (PWHT), ASME STP-PT-033

[8] Repair of Pressure Equipment and Piping

[9] National Board Inspection Code, NBIC

[10] Use of Corrosion Resistant Alloys in Oil Field, NACE TR1F192

[11] Welding Research Council Bulletin 481: The Effect of Post Weld Heat Treatment and Notch Toughness on Welded Joints and on Normalized Base Metal Properties of A516 Steel

[12] ASME BPVC sec II-part D.M

[13] Methods and Controls to Prevent In-Service Environmental Cracking of Carbon Steel Weldments in Corrosive Petroleum Refining Environments, NACE SP0472-2020

[14] Use of 9Cr-1Mo-V (Grade 91) Steel in the Oil Refining Industry, API TR 938-B

[15] Cracking of a Closing Weld in a Secondary Autothermal Reformer in a Mega Methanol Plant, D M Firth, Q Rowson, A Saunders-Tack, C Thomas, K Lichti and J Soltis, Quest Integrity NZL Limited.

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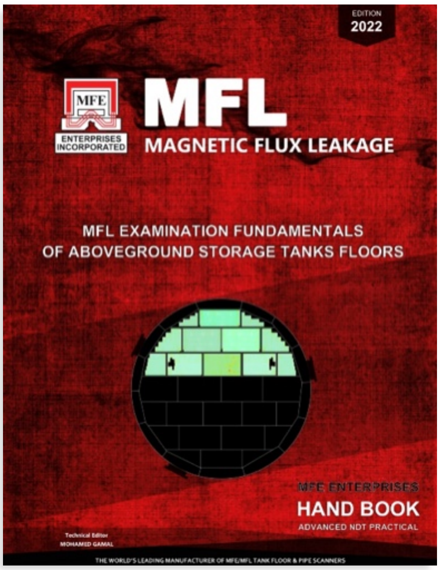

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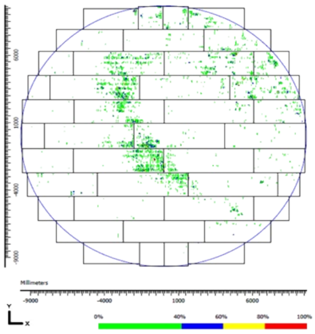

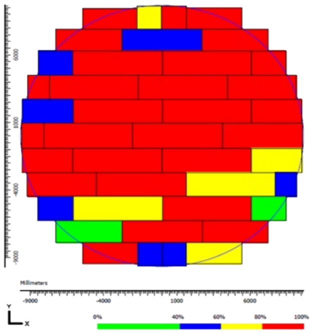

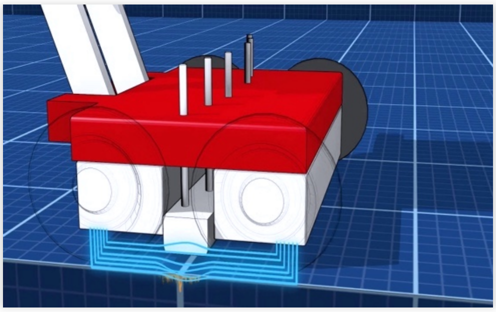

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Reliability Engineering
in the Era of Digitalization:
Challenges, Opportunities and the Future

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INTRODUCTION

Reliability engineering has long been a cornerstone of effective asset management, allowing equipment and systems to operate efficiently, effectively, and with high uptime. Traditionally, reliability engineering has relied on methodologies such as **Reliability-Centered Maintenance (RCM) and Failure Modes and Effects Analysis (FMEA)** to predict and prevent failures. However, the increasing pace of digitalization is altering the picture, ushering in new tools and technologies with the potential to transform how organizations tackle asset reliability. In the connected world of today, digitalization technologies such as the **Internet of Things (IoT), artificial intelligence (AI), and digital twins** are transforming industries. Such technologies bring both promising opportunities to improve reliability engineering practices and new challenges for companies to overcome.

The Evolution of Reliability Engineering

Reliability engineering has historically been concerned with the understanding and reduction of equipment failure risks. **RCM and FMEA** are some of the techniques that have been used to define critical failure modes and establish maintenance strategies for mitigating them. These methods depend largely on historical information, statistical modeling, and expert opinion to anticipate and avoid failures.

But the onset of digitalization has brought in a new paradigm. With **Industry 4.0** on the rise, reliability engineering is now utilizing cutting-edge technologies to transition from reactive and preventive **to predictive and prescriptive** maintenance. Technologies such as IoT sensors, AI-powered analytics, and digital twins are allowing organizations to monitor the health of assets in real-time, foresee failures before they happen, and optimize maintenance schedules.

Challenges in the Age of Digitalization

Though digitalization presents tremendous opportunities, there are also some challenges that companies must overcome:

1. Data Overload

The spread of IoT devices and sensors creates enormous amounts of data. For instance, an offshore oil rig alone can generate terabytes of data per day from sensors tracking equipment such as pumps, compressors, and turbines. Though useful, this data is overwhelming to handle and analyze. Organizations must invest in robust data management systems, such as **cloud-based systems and big data analytics software,** to gain meaningful insights. Organizations are in danger of data overload with no meaningful insights if they lack good data governance.

2. Skill Gaps

Implementation of new technologies calls for a talent pool with different skill sets. Engineers and maintenance staff must be trained in data analytics, machine learning, and digital tools to be able to fully utilize these technologies. For example, knowing how to read AI-powered predictive maintenance alerts or run digital twin simulations is specialized knowledge. Closing this skills gap is a prerequisite for successful digital transformation, and companies need to invest in **upskilling initiatives and partnerships with universities, educational institutions to ready their workforce.**

3. Integration Issues

Most organizations continue to use legacy systems that are incompatible with new digital tools. For instance, a factory might have machinery that is decades old and cannot be easily integrated with IoT sensors or AI platforms. New technologies may be difficult and expensive to integrate with current systems, and careful planning and execution are needed. Organizations need to embrace **modular and scalable solutions** that can be gradually integrated with legacy systems without interrupting operations.

4. Cybersecurity Risks

As assets are increasingly interconnected, they are also increasingly exposed to cyber threats. For instance, a cyberattack on an IoT sensor network of a power grid could cause large scale outages. Keeping critical asset information safe from cyberattacks is an increasing worry, and organizations need to adopt strong cybersecurity practices, including **encryption, multi-factor authentication, and frequent security audits,** to protect their operations.

Opportunities Brought by Digitalization

Despite these difficulties, digitalization presents considerable possibilities to improve reliability engineering procedures:

1. Predictive Maintenance

IoT sensors and AI powered analytics allow organizations to foresee equipment failures before they happen. For instance, General Electric (GE) utilizes Predix, its industrial IoT platform, to keep track of the health of gas turbines. Through real-time data analysis, GE can detect early warning signs of issues that could arise and plan maintenance in advance, minimizing downtime and expenses. Predictive maintenance has the potential to lower maintenance expenses by 20-30% and downtime by 50%, as per industry research.

2. Real-Time Monitoring

Digital technologies enable real-time monitoring of asset health. For example, Siemens utilizes IoT-enabled sensors to track the performance of wind turbines in real time. Real-time feedback gives visibility into equipment performance, allowing organizations to identify anomalies and attend to problems prior to their escalation. Real-time monitoring has the potential to enhance asset availability by 10-15%, based on Siemens' internal reports.

3. Enhanced Decision-Making

Big data and predictive analytics give organizations greater insight into the performance of assets. For instance, Shell applies AI-powered analytics to streamline maintenance on its offshore oil platforms. **Shell** can make better-informed maintenance scheduling decisions by analyzing historical and real-time data, which helps to cut costs and enhance reliability. Data-driven decision-making has the potential to **enhance operational efficiency by 15-20%,** based on Shell's case studies.

4. Digital Twins

Digital twins—virtual copies of physical assets enable organizations to simulate and optimize asset performance throughout their lifecycle. For instance, BP employs digital twins to simulate the performance of oil refineries. By running various scenarios in a virtual setup, **BP** can determine the most efficient maintenance strategies and enhance asset reliability. Digital twins have the potential to **lower maintenance expenses by 10-15% and increase asset uptime by 20%**, based on BP's internal statistics.

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Case Study: Shell's Digital Transformation in Reliability Engineering

Challenge:

Shell, a worldwide leader in the oil and gas sector, was confronted with major challenges in ensuring the reliability of its offshore drilling equipment. Conventional maintenance procedures were reactive, and this **resulted in regular unforeseen downtime** as well as costly maintenance. Shell required a method for **predicting equipment failure** and planning maintenance schedules.

Solution:

Shell adopted an **AI-based predictive maintenance** system **fueled by IoT sensors and machine learning algorithms**. The system gathered real-time data from offshore drilling equipment, including pumps and compressors, and utilized AI to interpret the data and foresee possible failures.

Results:

Less Downtime: Shell attained a **25% decrease in unplanned downtime** through the prediction of equipment failure prior to its occurrence.

Cost Savings:
Maintenance expenses were lowered by 20% because of optimized maintenance schedules.

Enhanced Reliability: Asset availability rose by 15%, resulting in increased production efficiency.

This case study illustrates the revolutionary power of digitalization for reliability engineering.

The Future of Reliability Engineering

As digitalization further develops, several emerging trends are set to influence the future of reliability engineering:

1. Blockchain for Asset Tracking

Blockchain technology provides a secure and transparent method of tracking asset performance and maintenance history. For instance, **Chevron** has been testing the use of blockchain to record the maintenance history of key refinery equipment. With blockchain, Chevron makes certain that each maintenance activity, inspection, and repair is recorded securely. This not only minimizes the likelihood of errors but also improves accountability.

In case a pump fails, engineers can easily trace the whole maintenance history of the pump, spot probable problems, and make knowledgeable decisions. Such openness can **cut maintenance errors by 15-20%** and compliance with safety procedures.

2. 5G Connectivity for Real-Time Monitoring

The advent of 5G networks is a game-changer, not least for the oil and gas industry. With its ultra-low latency and high data rate, 5G makes real-time monitoring of the equipment at a whole new level. ExxonMobil, for instance, has been testing 5G-enabled IoT systems at its refineries. By linking key assets such as compressors and distillation columns to a 5G network, **ExxonMobil** can track their performance in real time. When a compressor begins to vibrate excessively, the system warns engineers prior to failure.

This early intervention has enabled ExxonMobil to **decrease unplanned downtime by 30% and enhance overall asset reliability.**

3. Quantum Computing for Complex Reliability Analysis

Though in its nascent stages, quantum computing has tremendous potential for businesses that operate complex systems, including oil and gas refineries.

BP is among the first to venture into quantum computing for refinery operations. With quantum algorithms, BP can simulate the performance of its refinery assets under different conditions.

For instance, they can simulate how a distillation tower will react to a sudden rise in temperature or how a pipeline will react to pressure changes. Such simulations enable BP to optimize maintenance planning and minimize the likelihood of sudden failures. Initial trials indicate that quantum computing has the potential to **lower costs of maintenance by 10-15% and to increase asset uptime by 20%.**

CONCLUSION

The era of digitalization brings challenges but also opportunities for reliability engineering. Although integrating new technologies such as IoT, AI, and digital twins may be challenging, the potential gains in the form of predictive maintenance, real-time monitoring, and data-driven decision -making are tremendous. Companies that are able to overcome challenges and undergo digital transformation will be well placed to achieve improved reliability of assets, cost savings, and operational efficiency.

As the discipline of reliability engineering further develops, this much is certain: digitalization is not a trend—it is a paradigmatic change that will determine the future of asset management. By embracing these technologies, companies can tap into new dimensions of performance and achieve sustainable success in an increasingly competitive global marketplace.

References:

- ISO 55000 Standards for Asset Management
- Case Studies from Shell, Chevron, ExxonMobil, and BP

CONVERSATION FACTORS

LENGTH

1	Centimeter	=	0.3937	Inches	1	Inch	=	2.54	Cms
1	Meter	=	3.2808	Feet	1	Foot	=	0.3048	Meters
1	Kilometer	=	0.62137	Miles	1	Mile	=	1.60934	Kilometers
1	Kilometer	=	0.53996	Naut. Miles	1	Naut. Mile	=	1.852	Kilometers

AREA

1	Sq. meter	=	10.7639	Sq. Feet	1	Sq. Feet	=	0.092903	Sq. meters
1	Hectare	=	2.47105	Acres	1	Acre	=	0.404686	Hectares
1	Sq. Km	=	0.3861	Sq. Miles	1	Sq. Miles	=	2.58999	Sq. Kms
1	Sq. Km	=	247.105	Acres	1	Acre	=	0.004047	Sq. Kms

WEIGHT

1	Kilogram	=	2.20462	Pounds (lbs)	1	Pounds (lbs)	=	0.45359	Kilogram
1	Metric Ton	=	0.98421	Long Tons	1	Long Ton	=	1.01605	Metric Tons
1	Metric Ton	=	1.10231	Short Tons	1	Short Ton	=	0.907185	Metric Tons

VOLUME

1	Liter	=	0.2642	U.S. Gallons	1	U.S. Gallon	=	3.785	Liters
1	Liter	=	0.21997	U.K. Gallons	1	U.K. Gallon	=	4.546.9	Liters
1	Cu. Meter	=	6.2898	Barrels	1	Barrel	=	0.159	Cu. Meters
1	Barrel	=	42	U.S. Gallons	1	Barrel	=	158.97	Liters

STANDARD ENERGY EQUIVALENTS

1000 metric tons of oil equiv. (TOE)		1000 barrels of oil Equivalent (BOE)		1000 metric tons of coal equiv. (TCE)	
10	Tera calories (net)	1.43	Tera calories (net)	7	Tera calories (net)
41.9	Tera joules (net)	6	Tera joules (net)	29.3	Tera joules (net)
1.43	thousand metric tons of coal equiv.	0.204	thousand metric tons of coal equiv.	0.84	million cubic meters of natural gas
1.2	million cubic meters of natural gas	0.172	million cubic meters of natural gas	8.14	gigawatt hours of electricity
11.63	gigawatt hours of electricity	1.661	gigawatt hours of electricity	0.7	thousand barrels of oil equiv.
7	thousand barrels of oil equiv	0.143	thousand barrels of oil equiv.	27.78	billion (10^9) BTUs (net)
39.68	billion (10^9) BTUs (net)	5.674	billion (10^9) BTUs (net)		

SPECIFIC GRAVITY: VOLUME PER TON

Degrees API	Specific Gravity @ 60°F	Barrels per*	
		Met. Ton	Long ton.
25	0.904	6.98	7.09
26	0.898	7.02	7.13
27	0.893	7.06	7.18
28	0.887	7.1	7.22
29	0.882	7.15	7.27
30	0.876	7.19	7.31
31	0.871	7.24	7.36
32	0.865	7.28	7.4
33	0.86	7.33	7.45
34	0.855	7.37	7.49
35	0.85	7.42	7.54
36	0.845	7.46	7.58
37	0.84	7.51	7.63
38	0.835	7.55	7.67
39	0.83	7.6	7.72
40	0.825	7.64	7.76
41	0.82	7.69	7.81
42	0.816	7.73	7.85

SPECIFIC GRAVITY RANGES

	Specific Gravity	Barrels per metric ton
Crude Oils	0.80 - 0.97	8.0 - 6.6
Aviation Gasolines	0.70 - 0.78	9.1 - 8.2
Motor Gasolines	0.71 - 0.79	9.0 - 8.1
Kerosine's	0.78 - 0.84	8.2 - 7.6
Gas Oils	0.82 - 0.90	7.8 - 7.1
Diesel Oils	0.82 - 0.92	7.8 - 6.9
Lubricating Oils	0.85 - 0.95	7.5 - 6.7
Fuel Oils	0.92 - 0.99	6.9 - 6.5
Asphaltic Bitumen's	1.00 - 1.10	6.4 - 5.8

CALORIFIC VALUE OF FUELS

Rough Gross Values in Btu Per lb	
Crude Oils	18 300 - 19 500
Gasolines	20 500
Kerosine's	19 800
Benzole	18 100
Ethyl Alcohol	11 600
Gas Oils	19 200
Fuel Oil (Bunker)	18 300
Coal (Bituminous)	10 200 - 14 600
LNG	22 300

Multiples

micro = one millionth

milli = one thousandth

centi = one hundredth

dec = one tenth

deca = ten

hecto = one hundred

kilo = one thousand

mega = one million

giga = one billion (10^9)

tera = one trillion (10^{12})

Ref. Petroleum Magazine