CarestreamNDT

WHITE PAPER

The Effect of Radiographic Sensitivity for Selenium versus Iridium Radioisotopes for DDA and CR Systems

How Technological Surveyance and Innovation Management Potentialize the Digital Transformation of Imaging Processes

INTRODUCTION

At Carestream NDT we want to share not only our technological developments and product portfolio, but also the knowledge and practical experience that our staff obtains by working shoulder-to-shoulder with customers like you. We aim to share this knowledge and experience in a straightforward fashion so that our readers may find practical applications in their everyday activities.

This series is directed but not limited to NDE professionals in the following industries: Oil & Gas, Nuclear, Construction, Foundry and Castings, Energy Generation, Aerospace, Transportation, Automotive, Military and Defense, Agriculture, Art Restoration & Museum Artifacts, and NDE Services Companies.

CarestreamNDT

150 Verona Street
Rochester, NY 14608

www.carestream.com

Purposeful digital transformation

Technology and innovation management constitute two essential pillars of any successful digital transformation roadmap/strategy, nevertheless both pillars often are addressed from two extreme positions that impair a purposeful digital transformation: 1) technology and innovation management processes are partially articulated due to an incomplete understanding of their constituent elements or even to an intentional effort for not addressing a specific set of them, and 2) technology and innovation are pursued for their own sake without a real connection with the true purpose of the digital transformation effort.

In order to potentialize the value that technology and innovation management processes bring to digital transformation efforts and to achieve their true purpose, both shall be 1) profoundly understood in all their constituents as we will be describing in the following sections, and 2) aligned with all other organizational management systems such as occupational health and safety, quality, information security, energy, environmental, education, sustainability or social responsibility. All of them constitute means to an end, in this case, the purposeful digital transformation of NDE.

Along this article, we will analyze the use case associated with the effect on radiographic sensitivity for Selenium-75 versus Iridium-192 gamma sources for two sets of digital imaging acquisition technologies, digital detector arrays (DDAs) for radiography and imaging plates (IPs) for computed radiography (CR) systems.

Gamma sources 101

Brian White, Research Scientist and Level III Radiographer at Carestream NDT, explains the role of gamma-ray sources in industrial radiography in the following terms [13]: **"The industrial radiography inspection business searches for defects that may cause critical failures in components. It has long been understood that the quality of images produced via X-rays exceeds the quality of images produced by radioisotopes. However, radioisotopes are extremely prevalent for field radiography applications. Table 1 provides a summary of the three most common radioisotopes utilized in the industry. Images produced with gamma sources can be noisy due to the radiation spectrum of the radioisotope. As energy is increased the achievable contrast is decreased, and noise is increased due to scatter. The choice of Selenium should then result in images with improved detectability. However—how much of an improvement might we obtain with Selenium versus Iridium?"** This is the purpose of the use case developed by Brian White in collaboration with Dr. Mark Shilton from QSA Global, Inc., and described in detail in [13] and [14] that can be summarized as **"Radiographic sensitivity was determined for Selenium and Iridium radioisotopes used in combination with computed radiography and digital detector array radiography systems. Steel and aluminum plates with a range of penetrameter thicknesses were utilized to determine the point at which sensitivity could be achieved. Detectability**

improved with Selenium relative to Iridium across all conditions due to lower noise. Likewise, detectability improved with digital detector array radiography systems relative to computed radiography systems. Data from this investigation, as well as corresponding practical images, will be presented as part of this paper."

Source Type	Gamma Energy	Half-life and Activity Range	Average Emission Energy	Working range with steel	Emissivity rate
Selenium-75	97 to 401 keV	120 days 10 – 120 Ci	~215-230 keV	~0.118 to 1.14 inches ~3 to 29 mm	2.18 R/hr/Ci at 1 foot 5.4 × 10-5 mSv/h/MBq at 1 m
Iridium-192	206 to 612 keV	74 days 10 – 150 Ci	~370-380 keV	~0.47 to 2.48 inches ~12 – 63 mm	5.2 R/hr/Ci at 1 foot 1.3 × 10-4 mSv/h/MBq at 1 m
Cobalt-60	1.17 to 1.33 MeV	5.27 years	1.253 MeV	~1.97 to 5.9 inches ~50 – 150 mm	14.0 R/hr/Ci at 1 foot 3.5 × 10-4 mSv/h/MBq at 1 m

Table 1: Comparison of common radioisotopes used for industrial radiography, as described in White and Shilton [13] and [14].

ASNT Nondestructive Testing Handbook: Volume 3, Radiographic Testing provides the following details about selenium sources [1], **"The principal gamma-ray emissions of selenium 75 are shown in Table 1. The predominant emissions highlighted in the aforementioned list are utilized in gamma radiography. These ideally match the gamma-ray attenuation characteristics of smaller or lower density fixtures found in industries that have joints, such as pipelines, flanges, tanks, and their weldments. The useful working thickness range in copper, nickel, or steel alloys is commonly accepted as 3 to 29 mm (0.12 to 1.14 in.). This is variable, depending on the sensitivity requirement and imaging technique. Selenium 75 decays by electron capture with a half-life of 119.79 days to stable arsenic (…) Natural selenium (which is a highly toxic, volatile, reactive, and corrosive at high temperatures but is stable and insoluble in water at low temperatures) must be isotopically enriched by gas centrifugation before it can be used to make a practical gamma radiography source. Selenium 75 sources are tested to verify that they meet the same performance, safety, and regulatory standards that other gamma radiography sources meet, notwithstanding its properties. Selenium can be combined with one or more non-activating metals to form more stable metal alloys or composites. Radiography sources containing either elemental selenium 75 or metal alloy composites have undergone special fire tests to verify that they can withstand the conditions of a hypothetical 1200 °C (2192 °F) petrochemical fire without leakage (...) Radiography sources containing highly enriched elemental selenium 75 were first introduced in the mid-1990s; sources containing selenium 75 as a metal alloy composite were first introduced in 2000."**

Selenium gamma sources, paired with small, lightweight exposure devices, can be used in difficult-to-access locations where X-ray generators cannot go due to their size, weight, and power requirements. Se-75 is the preferred isotope for Small Controlled Area Radiograph (SCAR) exposure devices to enable the safety exclusion zone at worksites to be minimized during radiographic exposures in congested areas (reductions of safety exclusion zones can go up to 98%). For example: Se-75 radioisotope sources are used on offshore oil rigs and at power generation plants during outages to reduce non-occupational worker exposure.

The combination of a different type of gamma energy source, able to generate images enriched with an expanded palette of energy levels paired with the integration of a new set of technologies in DR and CR detectors, is an example of how proper technology management process and innovation can be obtain integrating proper technology partners focused in collaborative work with customers to our organization's network of excellence.

Energy (keV)	Gamma emission abundance (photons per 100 decays)
24.38	5.50
66.05	1.44
96.73	6.35
121.1	17.6
136.0	59.20
198.6	1.48
264.7	59.20
279.6	25.11
303.9	1.38
400.7	11.40
577.2	0.036

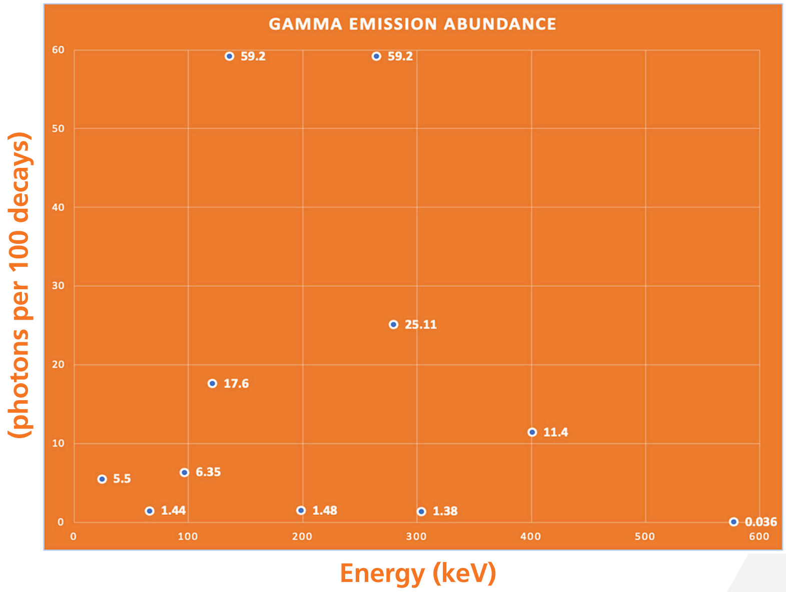


Table 2: Principal Gamma Ray-emissions of Selenium 75, as listed in [1].

Two sets of experiments with Se-75 and Ir-192 gamma sources were conducted; the first set comprehends obtaining images from a ½-inch stainless steel plate and from a 3/8-inch aluminum plate using both DDAs for DR images and IPs for CR images. The images obtained and associated sensitivity analysis are shown in images 4 to 10.

For computed radiography, the source-to-detector distance was 20-inches. A **CARESTREAM HPX-PRO** radiography system was utilized in conjunction with **INDUSTREX Version 5.1 Software** for image capture. Exposures were done at 7 R with an aim pixel intensity of 6000 through the base metal on a 16 bit linear scale. An HR type imaging plate was used. Images were captured at 50 mm pixel size with a photomultiplier tube setting of 10.

For digital detector array radiography, the source-to-detector distance was 29-inches. A **139 mm pixel pitch HPX-DR** radiography system was utilized in conjunction with **INDUSTREX Version 5.1 Software** for image capture. Exposures were done at 0.08 R for Iridium and 0.04 R for Selenium with an aim pixel intensity of 20,000 through the base metal on a 16 bit linear scale. Integration times were typically 5 seconds for Iridium and 14 seconds for Selenium, with 25 averaged frames.

DDA vs CR Images Comparison in a 1/2-inch Stainless Steel Plate

Figure 1: Experimental setup for 1/2-inch steel plate with a 139 mm pixel pitch HPX-DR DDA, as described in [13] and [14]

All Shots were taken with axial source emission so that the focal dimensions were effectively equivalent.

Using a Se-75 gamma Source

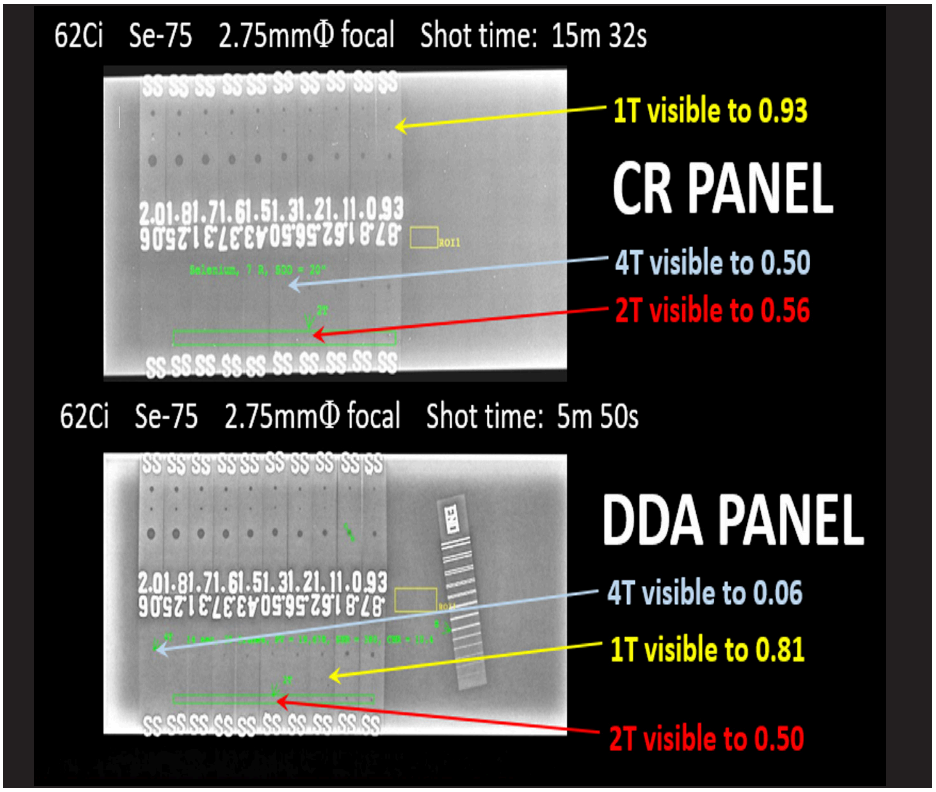


Figure 2: CR and DR comparison images of a 1/2-inch stainless steel plate obtained with a Se-75 gamma source, as described in [13] and [14]

Using a Ir-192 gamma Source

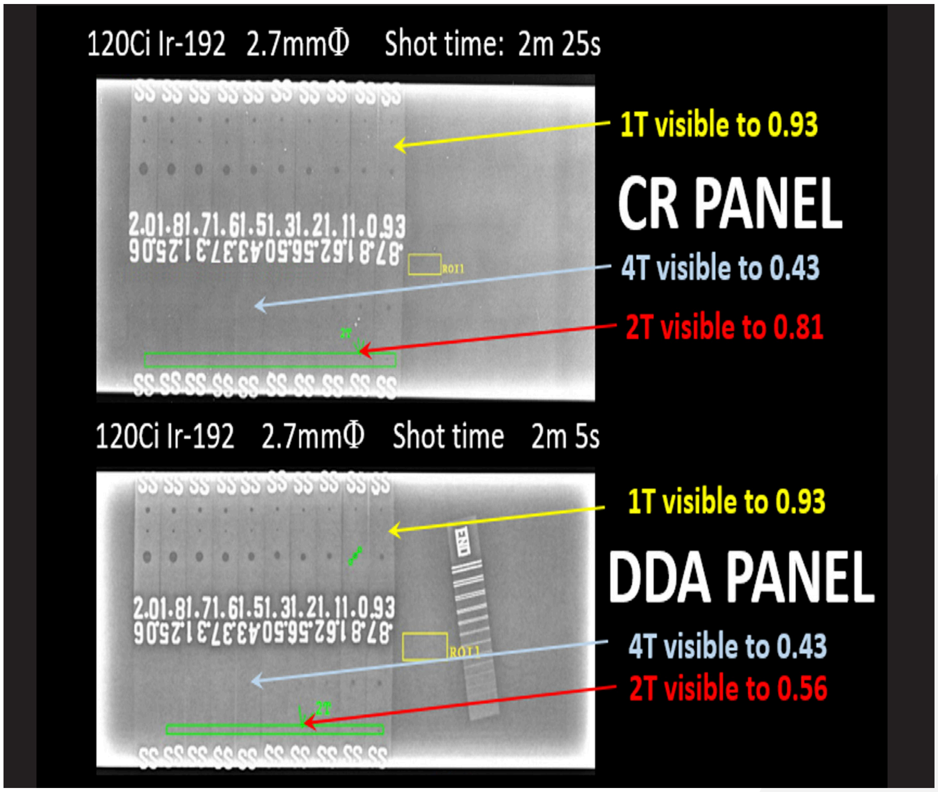


Figure 3: CR and DR comparison images of a 1/2-inch stainless steel plate obtained with a Ir-192 gamma source, as described in [13] and [14]

Analysis of 1/2-inch steel plate hole sensitivity

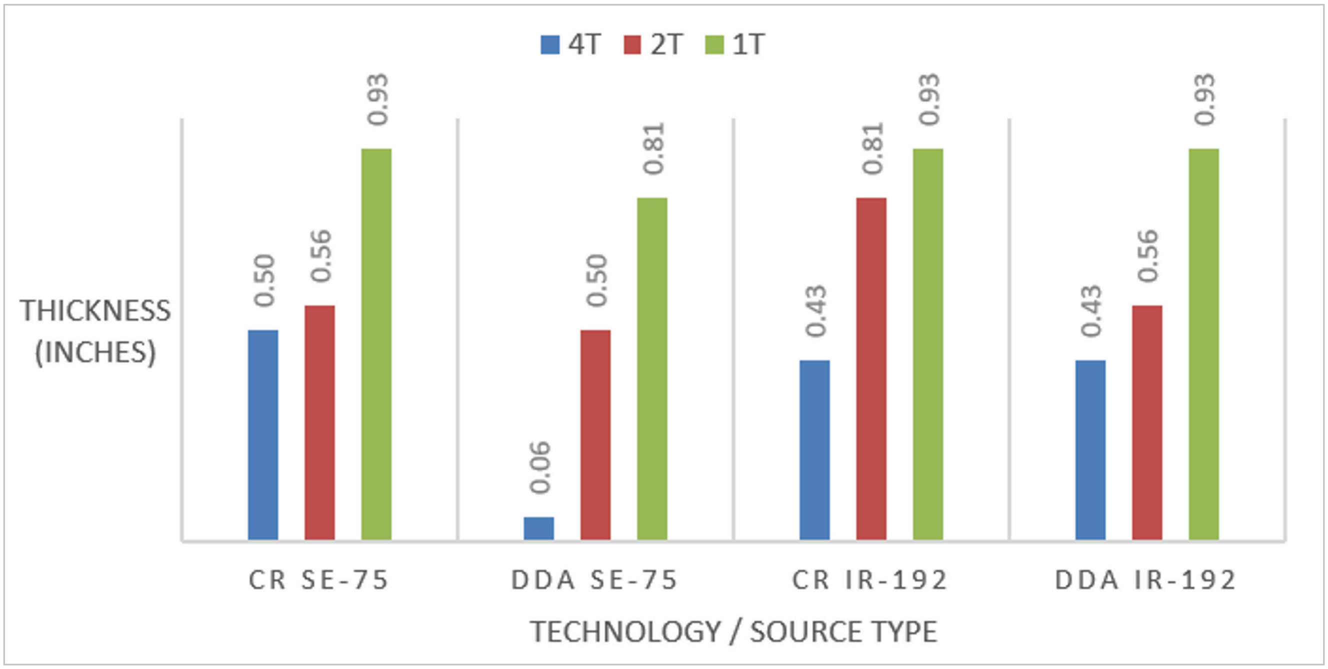


Figure 4: Hole Sensitivity comparison for CR and DR images of a 1/2-inch stainless steel plate obtained with Se-75 and Ir-192 gamma sources, as described in [13] and [14]

DDA vs CR Images Comparison in a 3/8-inch Aluminum Plate

All Shots were taken with axial source emission so that the focal dimensions were effectively equivalent.

Using a Se-75 gamma Source

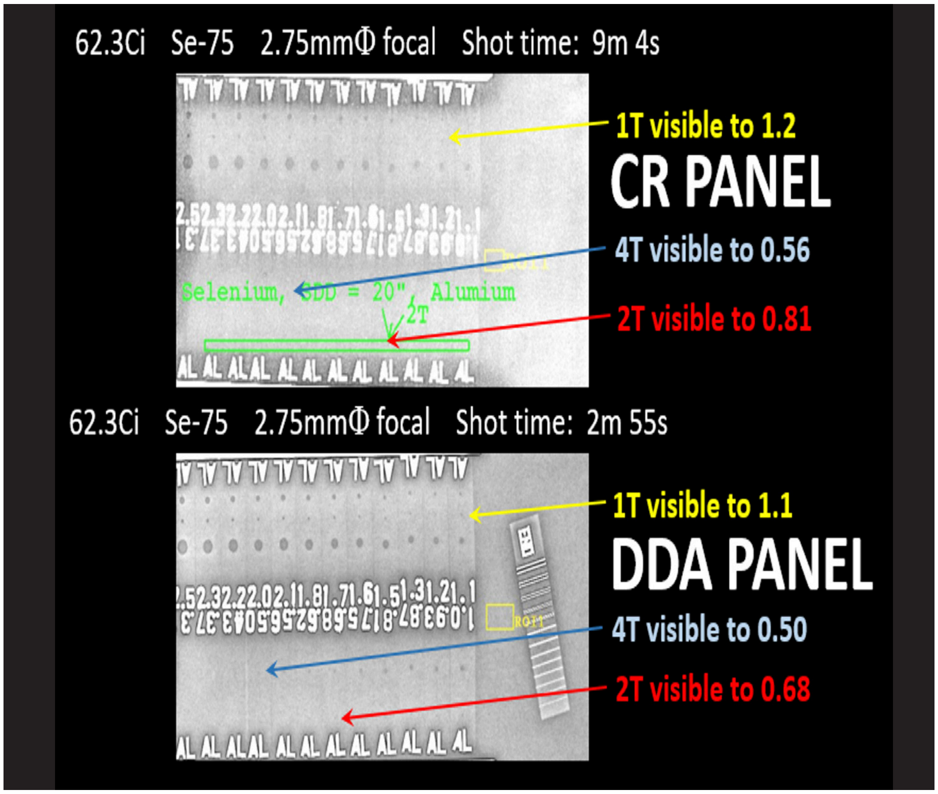


Figure 5: CR and DR comparison images of a 3/8-inch aluminum plate obtained with a Se-75 gamma source, as described in [13] and [14]

Using a Ir-192 gamma Source

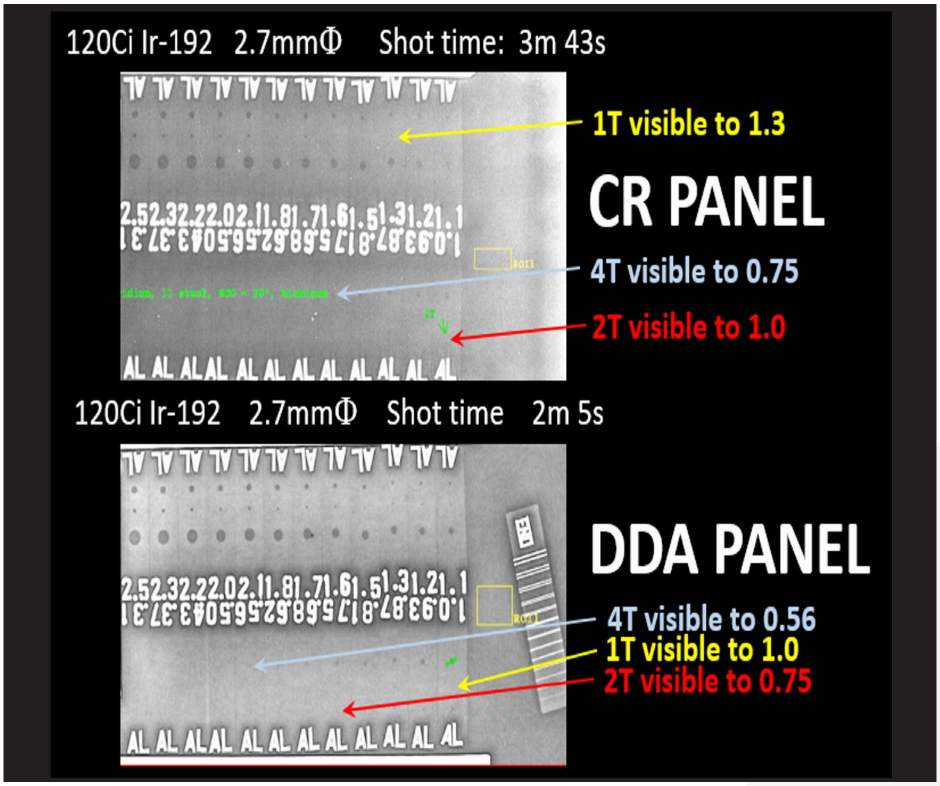


Figure 6: CR and DR comparison images of a 3/8-inch aluminum plate obtained with a Ir-192 gamma source, as described in [13] and [14]

Analysis of 3/8-inch Aluminum Plate Hole Sensitivity

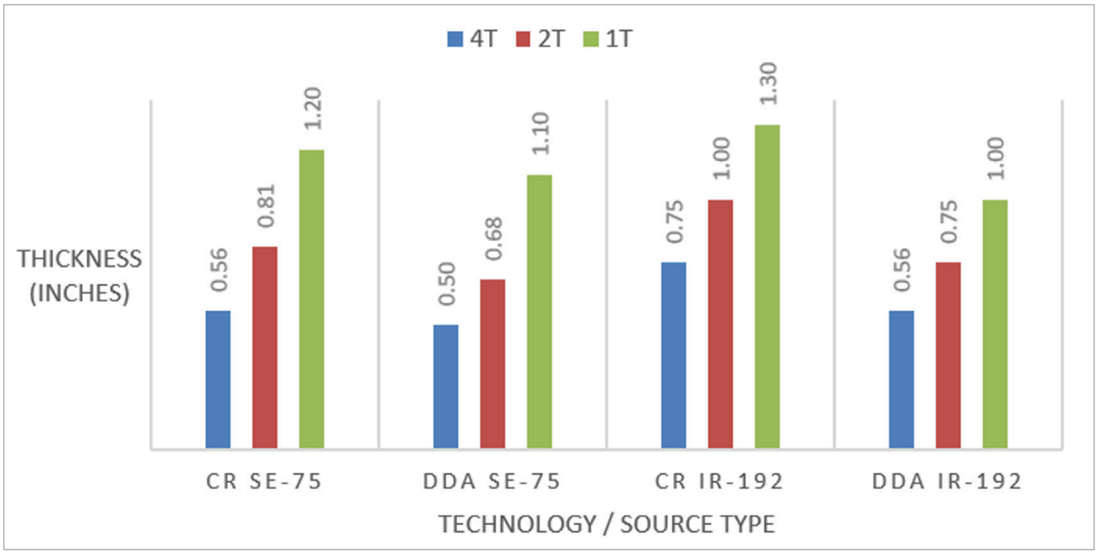


Figure 7: Hole Sensitivity comparison for CR and DR images of a 3/8-inch aluminum plate obtained with Se-75 and Ir-192 gamma sources, as described in [13] and [14]

Figure 8 resumes the difference in 2T hole contrast sensitivity of the two sets of images above in stainless steel and aluminum using both types of gamma sources and both sets of imaging technologies.

Analysis of 2T Contrast Sensitivity

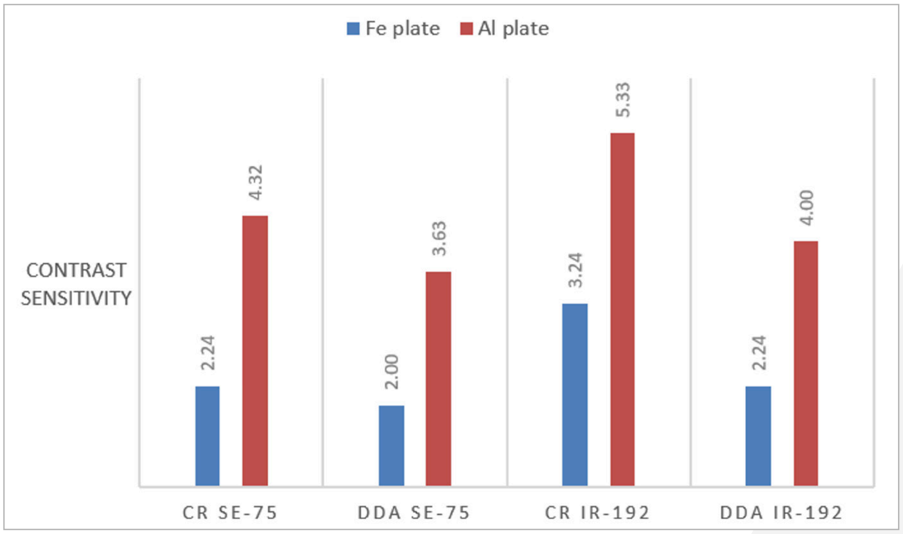


Figure 8: 2T Contrast Sensitivity comparison between CR and DR images from a ½-inch stainless steel plate and a 3/8-inch aluminum plate obtained with Se-75 and Ir-192 gamma sources, as described in [13] and [14]
Note: Please remember that a lower contrast sensitivity (CS) value means a better result in juxtaposition with contrast to noise ratio (CNR) where a higher value represents an improvement.

A parallel second set of tests comprehends obtaining images from a 2-inch, schedule 80, steel pipe (0.0216-inch wall thickness) using both DDAs for DR images and IPs for CR images. The images obtained and associated sensitivity analysis are shown in images from 12 to 14 and in **Table 3.**

DDA vs CR images comparison in a 2-inch schedule 80 steel pipe, 0.0216-inch wall thickness

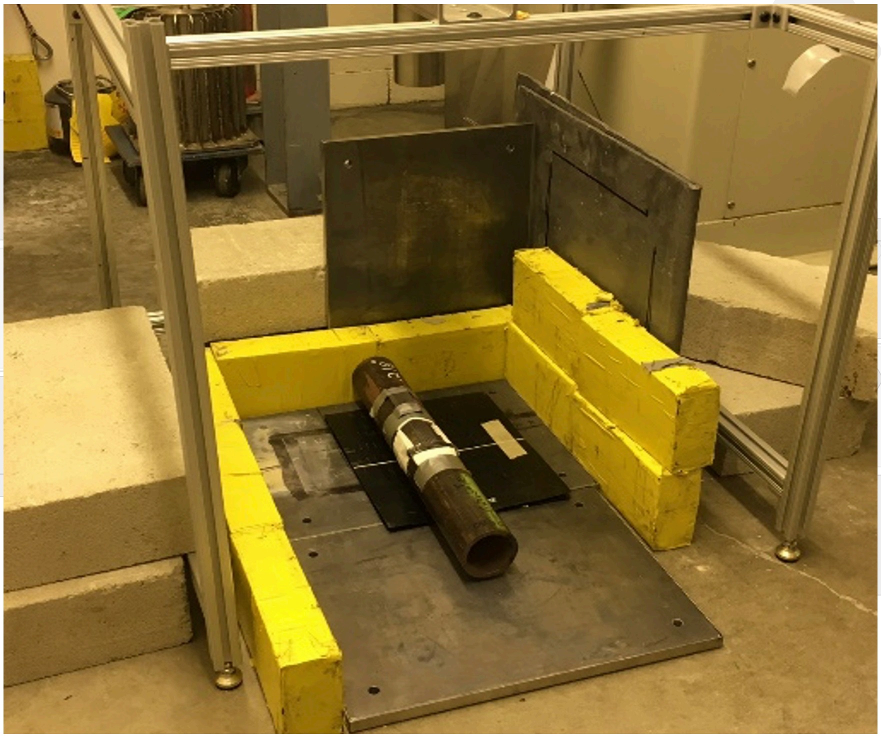


Figure 9: Experimental setup for a 2-inch pipe with CR Imaging Plates, as described in [13] and [14]

All Shots were taken with axial source emission so that the focal dimensions were effectively equivalent

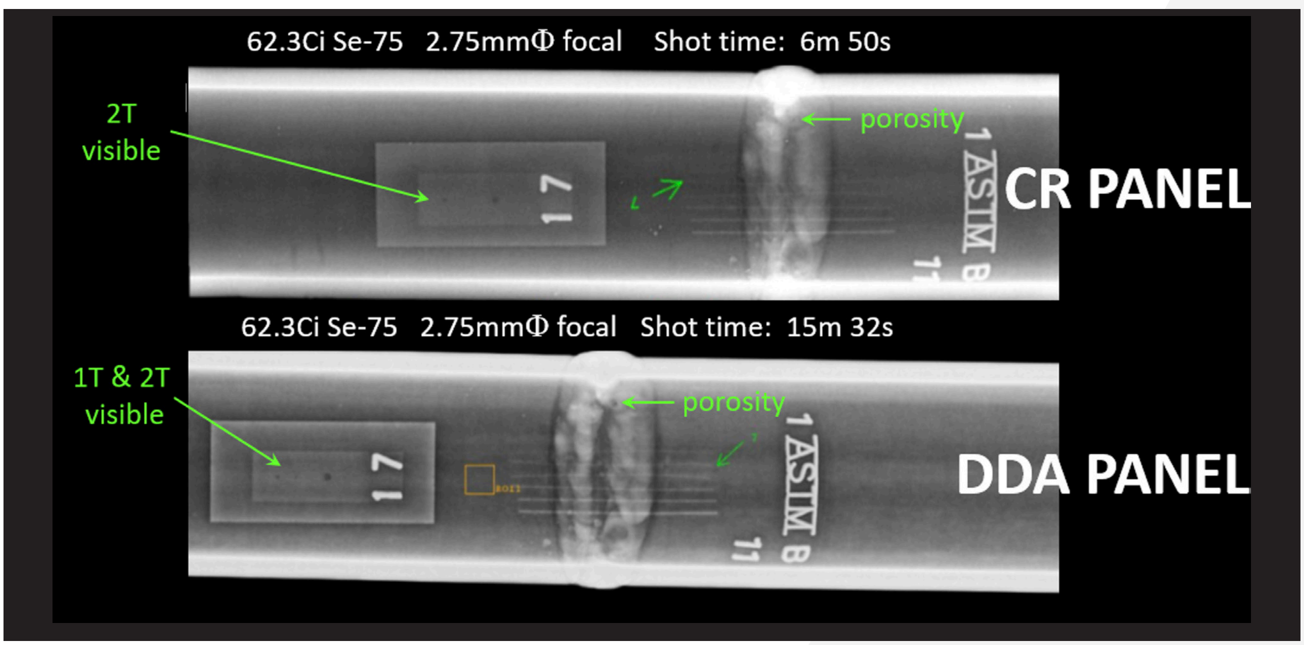


Figure 10: CR and DR comparison images of a 2-inch schedule 80 steel pipe obtained with a Se-75 gamma source, as described in [13] and [14]

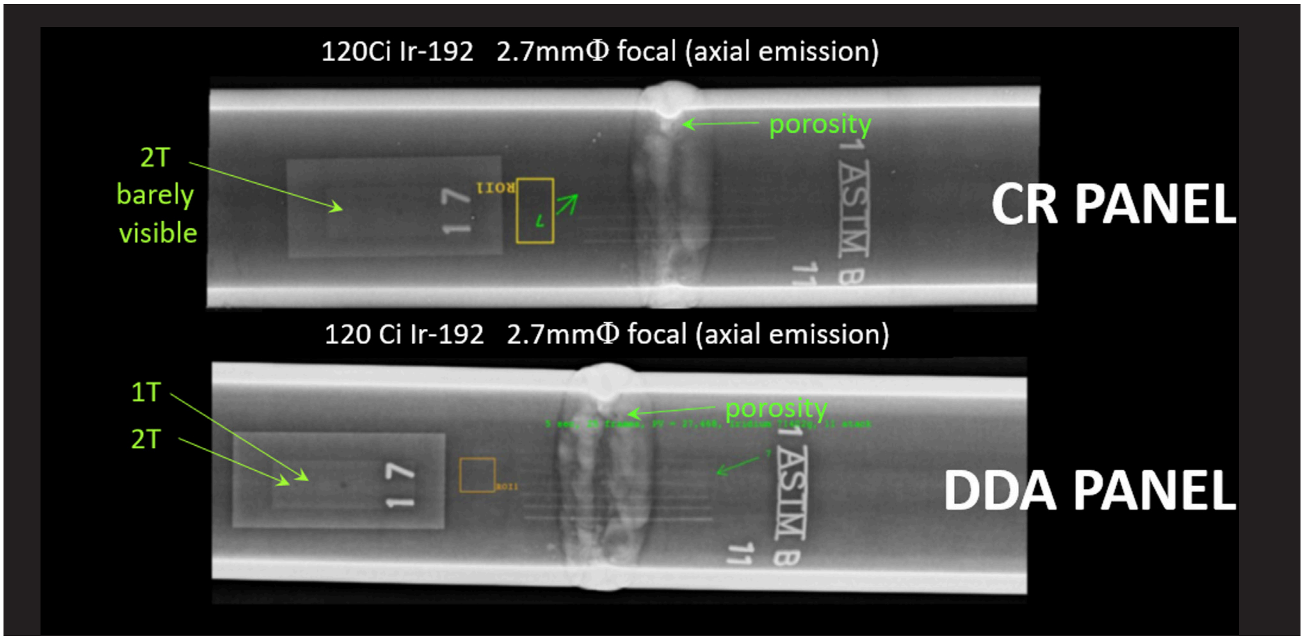


Figure 11: CR and DR comparison images of a 2-inch schedule 80 steel pipe obtained with a Ir-192 gamma source, as described in [13] and [14]

System	Gamma Source in Use	Observed Hole	Observed Wire
HPX-PRO	Se-75	2T	7
HPX-DR		1T	6
HPX-PRO	Ir-192	4T	7
HPX-DR		1T	7

Table 3: Analysis of a 2-inch schedule 80 steel pipe sensitivity of Selenium 75 vs Iridium 192 gamma sources, as described in [13] and [14]

Brian White resumes in the following terms the results obtained in both studies performed jointly with Dr. Shilton: "Radiographic detectability was best for Selenium radioisotopes used in conjunction with digital detector array systems because Selenium produced images with less noise. Likewise, digital detector array radiography systems produced images with reduced noise, which resulted in higher contrast-to-noise ratios and improved detectability. This can reduce shot time and extends the practical working life of sources."

An expanded definition of NDE 4.0

NDE 4.0 is defined in [5] by the NDE 4.0 Deployment Management Guidance Document developed by ICNDT's Special Interest Group (SIG) on NDE 4.0 as "Cyber-physical Non-Destructive Evaluation (including Testing); arising out of a confluence of industry 4.0 digital technologies, physical non-destructive testing methods, and business models; **to enhance inspection performance, integrity engineering, and decision making for safety, sustainability, and quality assurance, as well as provide relevant data required to improve design, production, and maintenance."**

This definition describes how NDE itself is transitioning from a niche role as a quality control support instrument to an invaluable knowledge-generating process for creating value through substantial improvements in business sustainability, quality, and safety by enabling optimal integration of non-destructive testing systems into the cyber-physical systems or smart factories to ensure full automation of all production and management processes. A checklist with the constituents of a basic portfolio of industry 4.0 technologies that may be relevant for NDE 4.0 initiatives is included in Table 6. You can use it as a diagnosis checklist to match them with your current needs, based in the industry where you participate and your geographic region.

The adoption of specific technologies and innovations to digitally transform systems and processes within organizations is always present at the core of NDE 4.0 initiatives. **Table 4** provides some examples of such use cases and value propositions:

Examples of Use Cases and Value Propositions for NDE 4.0 Initiatives	
Industry 4.0 for NDE: Adoption of Industry 4.0 technologies and innovations into NDE systems and processes	**NDE for Industry 4.0:** Adoption of NDE Technologies and innovations into Industry 4.0 systems and processes
1. Enhancing NDE capability and reliability through emerging technologies 2. Improving efficiency and effectiveness of inspections through better control 3. Improving NDE equipment using inspector and built-in application feedback 4. Improving inspector safety and inspection support through remote access 5. NDE for everybody	1. Quality assurance in the factory and the infrastructure of the future 2. Quality assurance of the additively manufactured components (and other small number of unique manufactured components) 3. NDE of drones and critical industrial robots 4. Continuous improvement through data mining 5. Data monetization

Table 4: A set of use cases and value propositions for NDE 4.0 Initiatives, adapted from Singh, and Vrana [9].

The use case that we are analyzing in this article, although at first glance may be classified as an Industry 4.0 for NDE use case that includes the adoption of Industry 4.0 technologies and innovations into NDE systems and processes through the digitalization of imaging processes and the integration of digital twins, threads and weaves, also may comprehend an NDE for Industry 4.0, if the assets that will be examined were manufactured using Industry 4.0 technologies such as additive manufacturing or Industry 4.0 equipment such as machining centers that support Internet of Industrial Things (IoIT) protocols.

An ecosystem perspective for NDE 4.0

Centered in the purpose of NDE 4.0 of enhancing inspection performance, integrity engineering, and decision making for safety, sustainability, and quality assurance, it is evident that the safety and integrity of assets can constitute the core of an NDE 4.0 Ecosystem as shown in **Figure 12** (by an asset we may signify any physical item, such as a piece of infrastructure, machine, industrial facility, building, power plant, or vehicle that requires examination to ensure its safety and integrity through time).

There exists a set of key stakeholders, both organizations and individuals, with an active contribution and direct impact on assets (blue elements in the diagram) and there is also a second set of support stakeholders that provides elements required for key stakeholders to achieve their purpose related with the asset (green elements in **Figure 12**). The amount of impact of each stakeholder may be affected by the dynamics of the industries in which they participate and by political, economic, social, technological, environmental, legal, normative, and innovation dynamics in the specific geographical regions where they operate, but it should be clear that those shareholders should be able to form and sustain value chains networks able to create value streams and feedback-loops that synergize and reinforce the NDE 4.0 ecosystem.

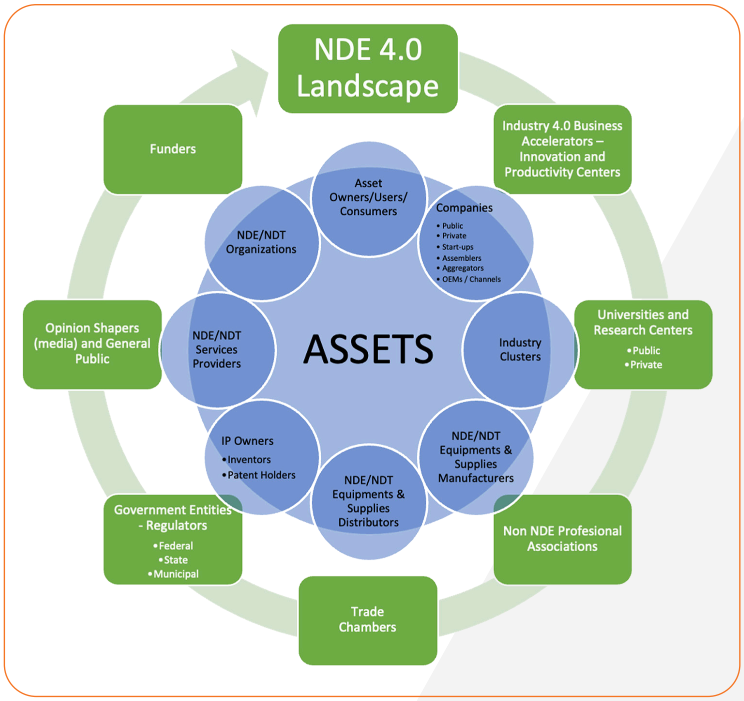


Figure 12: Constituents of an NDE 4.0 Ecosystem compiled from Fernandez [3], based on Singh and Vrana [10] [11].

Vrana, Meyendorf, Ida, and Singh, R in[9] emphasize the impact on digital transformation initiatives of having a clear ecosystem perspective for NDE 4.0: **"Digital Transformation is easier said than done. By now, you must have realized that the multi-disciplinary nature of the technology, and the multiple stakeholders in a successful application, calls for an ecosystem's perspective; where active contributors can appreciate and support each other's roles."**

For every organization it is of the highest relevance to detect key and support stakeholders in their own ecosystem with whom it is possible to establish strong support processes and alliances. **Figure 12** may be used as a checklist to analyze the actual constituents of the NDE ecosystem of our own organization and how this ecosystem may be reinforced and expanded.

The core of a technology management system

The NMX-GT-001-IMNC *"Technology Management System - Terminology"* standard [5] defines **technology as "the degree to which the potential value of a resource, which is the degree of usefulness or extrapolation of the benefits that a resource can generate, is obtained, through relative knowledge and abilities."** This is how knowledge and abilities combined are able to release the potential value of specific resources such as the components of NDE system, including energy sources of CR or digital radiography (DR) detectors.

This same standard defines **technology management as "organized knowledge about processes, methods, and practices that act on the planning, development, control, integration, and capitalization of resources, for the implementation of technological changes or innovations in companies and institutions with the purpose of maintaining or improving the competitive position,"** portraying the profound interconnection between technological change and innovation.

Finally, NMX-GT-001-IMNC provides the building blocks or constituents of a technology management system through the following definition: **"An organization's management system for surveilling, planning, aligning, enabling, protecting, implementing, and controlling technology."**
Figure 13 provides a graphic depiction of how those building blocks are interconnected:

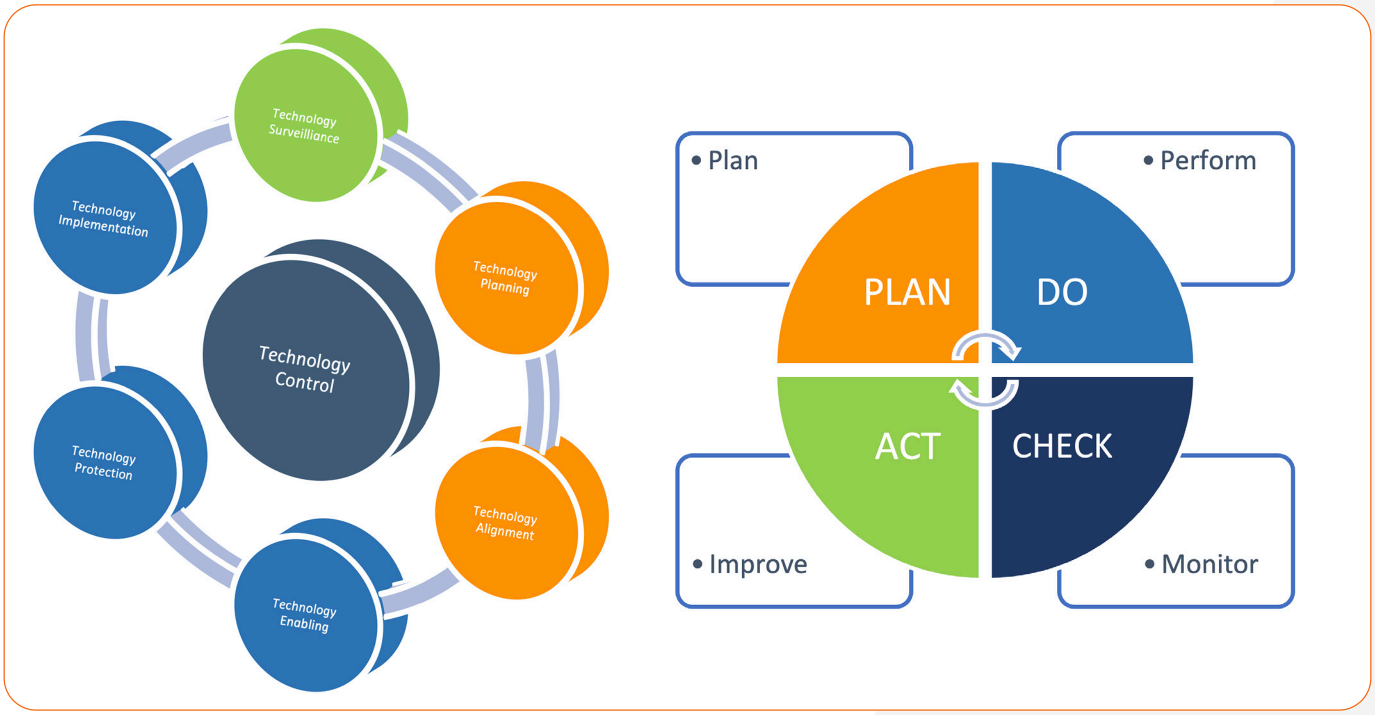


Figure 13: Constituents of a technology management system, adapted from NMX-GT-001-IMNC and based on the Continuous Improvement PDCA Cycle (Plan-Do-Check-Act) [5].

Projects and initiatives on a digital transformation initiative should be managed with rigor of technology or innovation management depending upon the degree of uncertainty associated with the initiative. 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:

   i. technology acquisition (purchase, licensing, alliances, and other applicable methods)
   ii. technology assimilation
   iii. technology development (technological research and development, technology up-scaling, and other applicable instances)
   iv. technology transfer
   v. technological projects portfolio management
   vi. technology-involved personnel management
   vii. financial resources management, and
   viii. 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 implementation:** 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.

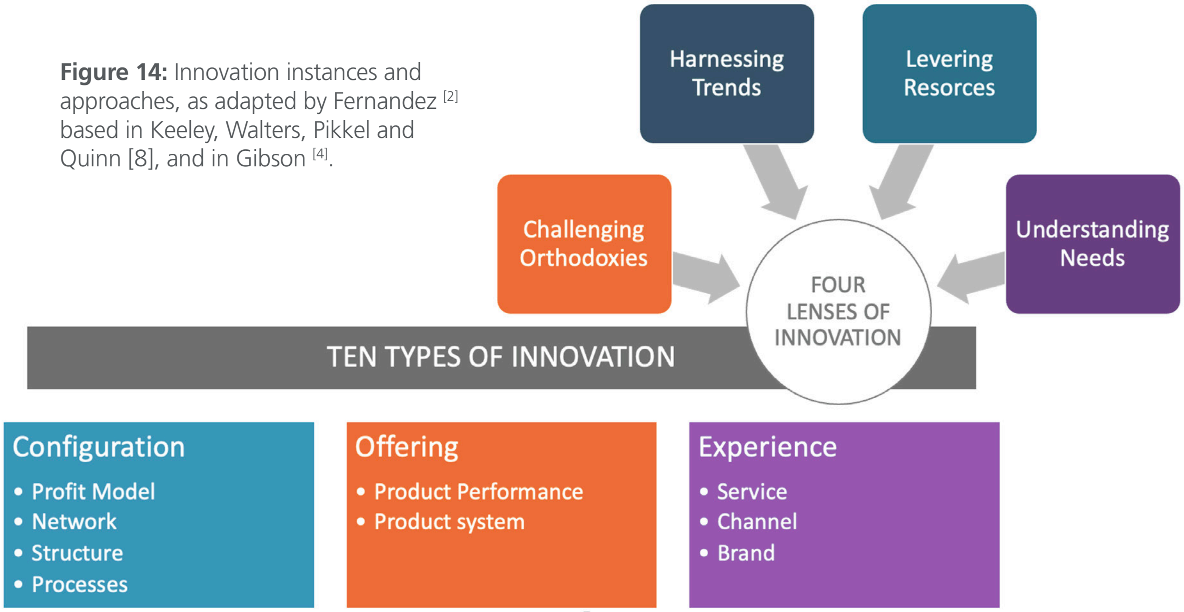
g) **Technology control:** The periodic and systemic oversight of all the constituents of the technology management system in order to create a series of continuous improvement feedback loops between them.

The evolution of Technologies associated with DDAs, IPs, DR and CR systems, DR and CR Software, gamma sources manufacturing, and gamma source projectors design should be closely monitored through the series of processes that constitute the technology management systems starting with the technological surveillance process in order to obtain the most value of any technology deployment process associated with the technologies described above.

Where we can innovate

ISO 56000 standard on *Innovation management — Fundamentals and vocabulary* [7] highlight the importance of innovation: **"An organization's ability to innovate is recognized as a key factor for sustained growth, economic viability, increased well-being and the development of society. The innovation capabilities of an organization include the ability to understand and respond to changing conditions of its context, to pursue new opportunities, and to leverage the knowledge and creativity of people within the organization in collaboration with external interested parties."** NDE 4.0 also requires significant innovation that entails a matchmaking between needs and ideas. Detailed guidance for innovation management systems can be found in ISO 56002, but we provide a starting point in **Figure 14:** a set of four lenses and 10 instances to start guiding your innovation interest with concrete answers to HOW and WHERE you can look for innovation opportunities. Both lenses and instances have a profound connection with our use case.

Figure 14: Innovation instances and approaches, as adapted by Fernandez [2] based in Keeley, Walters, Pikkel and Quinn [8], and in Gibson [4].



Lens for Innovation	Reflection question
Challenging Orthodoxies	What if the dominant conventions in your field, market, or industry are outdated, unnecessary, or just plain wrong?
Harnessing Trends	Where are the shifts and discontinuities that will, now and in the future, provide the energy you need for a major leap forward?
Leveraging Resources	How can you arrange existing skills and assets into new combinations that add up to more than the sum of their parts?
Understanding Needs	What are the unmet needs and frustrations that everyone else is simply ignoring?

Table 5: Four Reflection questions to detect Innovation instances, as adapted by Fernandez [2] based in Gibson [4].

In the use case we are analyzing, it leverages the four lenses of innovation because it is simultaneously challenging orthodoxies, harnessing trends, leveraging resources and understanding needs. It also centers innovation not only in the configuration of the examination processes but also in the structure of the manufacturing processes, in the products system, and finally in the experience of service to customers.

How we can innovate

Based in this ecosystem perspective, it is evident that any organization to succeed toward the future needs to reinforce in the present time their value networks with stakeholders able to provide both sound and trustworthy technology paired with relevant innovations developed in collaborative efforts constituting a series of networks of excellence, described as one of the best practices for NDE 4.0 adoption in [9]: **"With so many diverse technologies coming together, and a need for new skills set, it is difficult for most organization to have all the talent in-house. (…) Even in large corporations where executives believe to be self-sufficient are now realizing the need for having a Network of Excellence. Strategic partnerships with universities, freelance consultants, small tests facilities, training centers, and supply chain can add considerable value to the innovation process. Each of this can compensate for the weakest link in the in-house innovation value chain."**

Carestream NDT's portfolio of products and services, constituted by sound and trustworthy technology paired with relevant innovations developed in collaborative efforts with customers, fits as an added-value partner for their actual and potential customer's networks of excellence.

How to make use of the information in this post

Here are some supplementary information resources from Carestream NDT's products and services portfolio:

Products:

- HPX-DR 3543 PE Non-Glass, Large Format Detector
- HPX-DR 2530 PH High-Resolution, Compact Detector
- HPX-DR 2530 PC High-Speed, Compact Detector
- HPX-DR 4336 GH High-Resolution, Large Format Detector
- HPX-DR 2329 GK, High-Resolution, Compact Detector

- HPX-PRO Portable Digital System
- INDUSTREX HPX-1 Plus Digital System
- INDUSTREX Flex GP, HR and XL Blue Digital Imaging Plates
- HPX-1 Diagnostic Tool & HPX-1 Digital Plate Carrier

- INDUSTREX Digital Viewing Software
- NDT Archive Solution

- INDUSTREX Films
- INDUSTREX Chemicals for Automatic Processing
- INDUSTREX Chemicals for Manual Processing
- INDUSTREX Eco-Friendly Chemicals
- INDUSTREX Processors

INDUSTREX Digital Radiography (DR)

INDUSTREX Computed Radiography (CR)

INDUSTREX Film

Training Services:

- **Advanced Industrial Radiographic Training Academy**
  Computed Radiography - 40 Hour Online Course
  Digital Imaging - 40 Hour Classroom Training

Other Carestream NDT Resources:

- Carestream NDT Virtual NDT Showcase
- Carestream NDT Resource Center

Resources from ASNT:

- Radiographic Interpretation, Revised Edition 2020:
https://www.asnt.org/Store/ProductDetail?productKey=826c3c22-42a3-4250-9040-913d40aa0946

- Nondestructive Testing Handbook, fourth edition: Volume 3, Radiographic Testing:
https://www.asnt.org/Store/ProductDetail?productKey=83ea27b3-d68f-483d-9354-e447ef2b3915

A basic portfolio of relevant industry 4.0 technologies for NDE 4.0 may include, but is not limited to, those included in the following table:

Technology	Is relevant for me?
Digitization, Digitalization, Digital Transformation, and Informatization	❏ Yes ❏ No
Digital Twins, Digital Threads and Digital Weaves	❏ Yes ❏ No
IIoT: Industrial Internet of Things and the Infrastructure	❏ Yes ❏ No
Semantic Interoperability, Ontologies	❏ Yes ❏ No
Industry 4.0 Data Processing	❏ Yes ❏ No
5G	❏ Yes ❏ No
Blockchain	❏ Yes ❏ No
Cloud	❏ Yes ❏ No
Artificial Intelligence (AI), including machine learning and deep learning.	❏ Yes ❏ No
Big Data	❏ Yes ❏ No
Mobile Devices, Handheld and Small-Size Computers	❏ Yes ❏ No
Quantum Computers	❏ Yes ❏ No
Extended Reality (XR, including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR))	❏ Yes ❏ No
Additive Manufacturing	❏ Yes ❏ No

Table 6 – A basic portfolio of relevant industry 4.0 technologies for NDE 4.0 initiatives, as proposed by Singh and Vrana in [10].

References:

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