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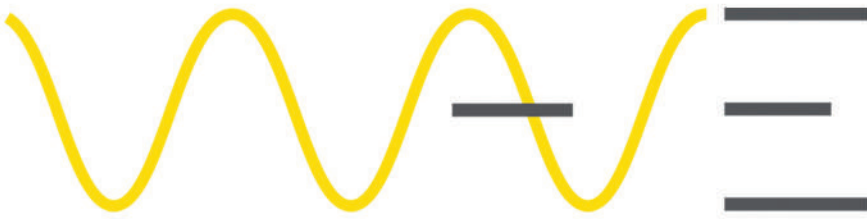
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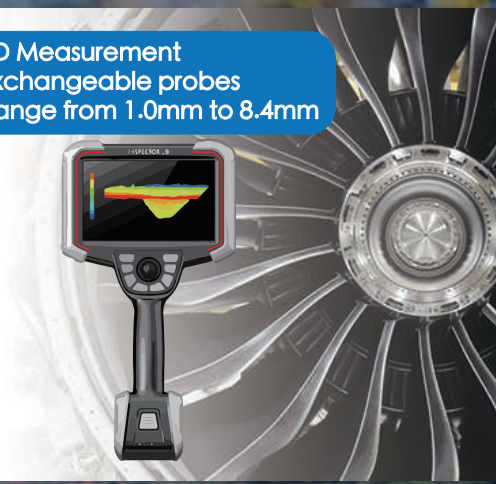
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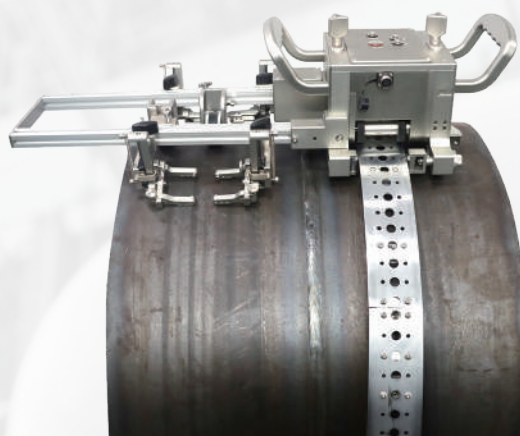


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# Pipeline Inspection in Oil & Gas



By Onur ÖZUTKU

Pipelines form the backbone of fluid transfer systems in oil and gas terminals. They connect storage tanks, pumping stations, marine loading arms, truck and rail loading racks, and processing units. Through these interconnected networks, large volumes of hydrocarbons are transported continuously under controlled pressure and flow conditions. Because these pipelines handle flammable, hazardous, and often high-value products, maintaining their integrity is essential for safe, environmentally responsible, and efficient terminal operations.

Pipeline failures in terminal environments can have severe consequences, including fire or explosion hazards, environmental contamination, product loss, operational disruptions, and reputational damage. For this reason, systematic pipeline inspection and integrity management programs are fundamental elements of terminal operation and maintenance practices. A well-designed inspection strategy allows operators to identify degradation mechanisms at an early stage and take preventive measures before failures occur.

Because of these complexities, pipelines within terminals require a structured inspection and monitoring program to ensure long-term reliability.

## 1. Common Degradation Mechanisms in Terminal Pipelines

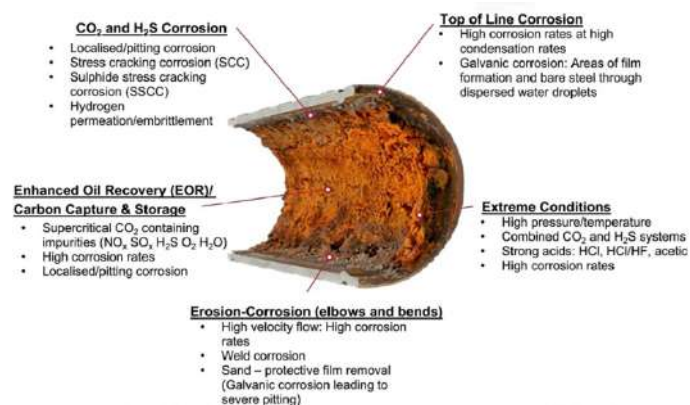
Understanding the typical failure mechanisms affecting pipelines is essential for designing an effective inspection program.

### 1.1 Internal Corrosion

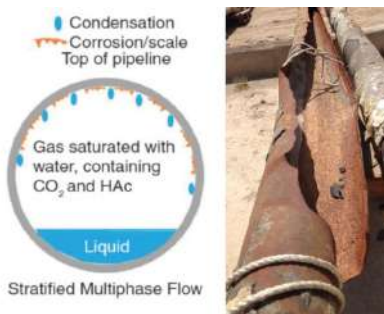
Internal corrosion occurs when chemical or electrochemical reactions between the pipeline material and the transported fluid gradually degrade the internal pipe wall, leading to metal loss and potential integrity issues.

In hydrocarbon pipelines, this type of corrosion is often driven by water contamination within the hydrocarbon stream, which can create localized electrochemical cells that accelerate metal dissolution.

Dissolved gases such as hydrogen sulfide (H<sub>2</sub>S) and carbon dioxide (CO<sub>2</sub>) can further exacerbate corrosion by forming acidic solutions in contact with the metal surface. Microbiologically influenced corrosion (MIC), caused by the activity of certain bacteria that produce corrosive byproducts, can lead to highly localized pitting and material loss.



Additionally, acidic or sulfur-containing compounds naturally present in crude oil may attack the pipe material over time, gradually thinning the wall and reducing structural integrity. If left undetected, internal corrosion can result in leaks, ruptures, and operational downtime, making routine monitoring and mitigation strategies such as corrosion-resistant materials, and internal coatings essential for safe pipeline operation.



Corrosion top of pipeline

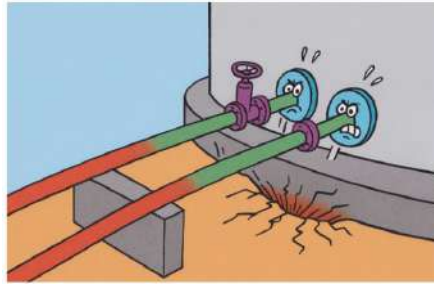
### 1.2 External Corrosion

External corrosion develops on the outer surface of pipelines and is primarily driven by environmental exposure and the degradation of protective barriers. The most immediate contributing factor is damage or deterioration of protective coatings, which normally shield the metal from direct contact with moisture and oxygen.



External Surface Corrosion

When coatings are compromised, water, oxygen, and other corrosive agents in the environment can interact with the pipe surface, initiating and accelerating the corrosion process.



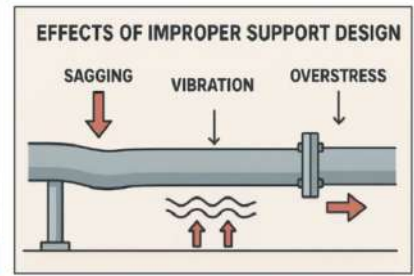
In buried pipelines, soil conditions such as acidity, moisture content, and chemical composition play a critical role in the rate and severity of corrosion. Stray electrical currents from nearby electrical systems can also induce corrosion through electrochemical reactions on the pipeline surface. Additionally, ineffective or improperly maintained cathodic protection systems which are designed to counteract corrosion by providing a controlled electrical current can leave sections of the pipeline vulnerable. Over time, these factors can result in significant material loss, weakening the structural integrity of the pipeline and increasing the risk of leaks or failures if not detected and mitigated through regular inspection and maintenance.



Trapped Water Corrosion

### 1.3 Mechanical Damage

Mechanical damage in pipelines can arise from a variety of operational and external factors that introduce abnormal stresses or physical impact on the system.



One of the most common causes is impact from vehicles or mobile equipment operating near the pipeline, particularly in industrial facilities where forklifts, trucks, or heavy machinery frequently move through pipe rack areas. Damage may also result from improper pipe supports or misalignment, which can create uneven load distribution and lead to localized stresses over time. Thermal expansion and contraction during normal operating cycles can generate significant stresses if expansion allowances are insufficient or if the pipeline is improperly constrained. In addition, vibrations generated by pumps, compressors, or other rotating equipment can gradually weaken pipe connections, supports, and welds when not properly isolated or dampened. Mechanical damage can also occur during maintenance activities, especially when work is carried out without adequate protection of nearby piping systems or when improper tools and handling practices are used. Over time, these factors may lead to deformation, cracks, or structural weakening of the pipeline, potentially compromising the integrity and safe operation of the system.

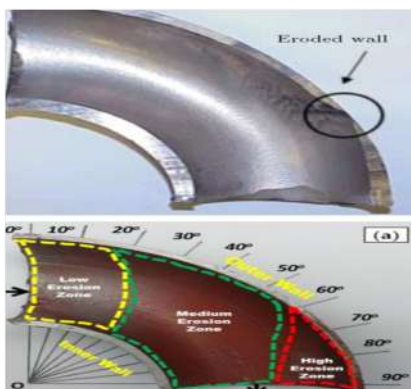


Thermal Expansion

### 1.4 Erosion

Erosion is a form of mechanical wear caused by the high-velocity flow of fluids carrying solid particles, liquid droplets, or other entrained materials that repeatedly impact the internal surface of a pipeline. Over time, these impacts remove small amounts of material from the pipe wall, gradually thinning the metal and potentially leading to loss of containment if not detected in time.

In terminal pipelines, erosion is most observed in areas where the flow velocity increases or where turbulence is generated. Typical locations include pump discharge lines, pipe bends, reducers, tees, and control valves. In these sections, changes in flow direction or cross-section create localized turbulence and accelerate the fluid stream, increasing the intensity of particle impingement on the pipe wall.



The severity of erosion depends on several factors, including fluid velocity, particle size and concentration, material hardness, and flow regime. Even relatively small particles can cause significant damage when transported at high velocity over extended operating periods. In multiphase systems, such as lines carrying liquid and vapor phases, droplets can also contribute to erosive wear.

To mitigate erosion risks, proper pipeline design, controlled flow velocities, material selection, and periodic inspection methods such as ultrasonic thickness measurements are essential. Early identification of erosion-prone locations allows operators to implement preventive maintenance strategies before significant wall loss occurs.

## 2. Pipeline Inspection Techniques

A comprehensive pipeline inspection program typically combines several non-destructive examination (NDE) methods to detect different types of defects.

### 2.1 Visual Inspection

Visual inspection is one of the most fundamental, yet essential inspection techniques used in pipeline integrity management. It involves the systematic examination of pipelines and associated components to identify visible signs of damage, deterioration, External corrosion or abnormal operating conditions. During these inspections, particular attention is given to external corrosion that may develop on the pipe surface due to environmental exposure, as well as damage or degradation of protective coatings that normally serve as the first barrier against corrosion. Inspectors also evaluate the adequacy and condition of pipe supports, since poor or misaligned supports can lead to excessive stress and long-term structural problems.



In addition, the pipeline is checked for any form of deformation such as dents or bending that could indicate mechanical stress or external loading. The integrity of flanges and the condition of gaskets are also carefully assessed because leakage or misalignment in these components may compromise system tightness. Finally, inspectors look for evidence of mechanical impact or external interference, such as marks caused by vehicles, tools, or nearby construction activities. Although visual inspection is a relatively simple and low-cost method, when carried out regularly and systematically it can provide valuable early warning signs of integrity issues, allowing corrective actions to be implemented before minor defects evolve into serious operational or safety risks.

### 2.2 Ultrasonic Thickness Measurement (UT)

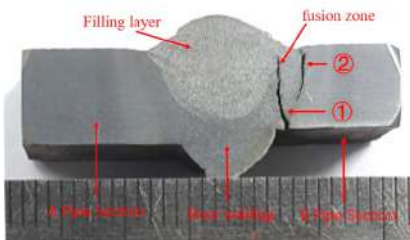
Ultrasonic testing is one of the most widely used techniques for monitoring corrosion in pipelines. Using ultrasonic waves, inspectors can measure the remaining wall thickness of pipes without removing them from service.



Thickness measurements are typically taken at predefined corrosion monitoring locations (CMLs). By repeating measurements periodically, engineers can calculate corrosion rates and estimate the remaining service life of the pipeline.

### 2.3 Radiographic Testing (RT)

Radiographic Testing (RT) is a non-destructive examination technique that uses X-rays or gamma rays to evaluate the internal structure of pipeline welds and pipe sections without damaging the material. The method works by passing radiation through the component and capturing the transmitted rays on a detector or radiographic film, producing an image that reveals variations in material density. These variations allow inspectors to identify internal defects that cannot be detected through visual inspection alone.



Radiographic testing is particularly effective in detecting weld-related imperfections such as lack of fusion between weld metal and base material, internal porosity formed by trapped gases during welding, cracks that may develop due to thermal stresses or material defects, and slag inclusions resulting from improper welding practices. Because of its ability to provide a clear representation of internal weld quality, radiography is widely used during pipeline construction, fabrication, and major repair activities to verify that welds meet required quality and safety standards before the pipeline is placed into service.

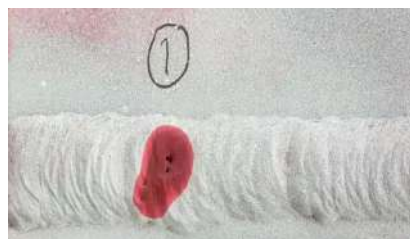
### 2.4 Magnetic Particle Inspection (MPI)

Magnetic particle inspection is used to detect surface and near-surface cracks in ferromagnetic materials. It is frequently applied to welded joints, flanges, and fittings where stress concentrations occur.



### 2.5 Dye Penetrant Testing (PT)

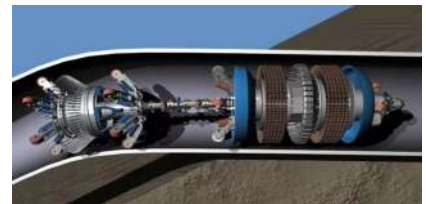
Dye penetrant testing is another method used to detect surface-breaking cracks. A liquid penetrant is applied to the surface and allowed to seep into cracks, which are then revealed using a developer.



This method is often used in combination with other inspection techniques during maintenance shutdowns.

### 2.6 In-Line Inspection (Intelligent Pigging)

In-line inspection (ILI), commonly referred to as intelligent pigging, is an advanced non-destructive inspection technique used to assess the internal condition of pipelines while they remain in operation. In this method, specialized inspection tools known as intelligent pigs travel through the pipeline, propelled by the product flow, and collect detailed data on the pipe's structural integrity. These tools are equipped with sophisticated sensors capable of identifying a wide range of defects, including corrosion, metal loss, cracks, dents, and geometric deformations that may affect pipeline performance and safety.



Several technologies are commonly employed in intelligent pigging systems, such as Magnetic Flux Leakage (MFL) for detecting metal loss and corrosion, ultrasonic inspection for accurately measuring wall thickness and identifying internal defects, and caliper tools that measure pipeline geometry to detect dents, or other dimensional changes. Although pipelines within storage terminals are often shorter and contain more bends, valves, and complex routing compared to long-distance transmission pipelines, intelligent pigging can still be effectively applied in certain transfer lines or straight sections where pipeline geometry and operational conditions permit the passage of inspection tools.

### 2.7 Guided Wave Testing (GWT)

Guided Wave Testing (GWT) is a non-destructive inspection technique used to evaluate the condition of pipelines over relatively long distances from a single test location. The method works by introducing low-frequency ultrasonic waves into the pipe wall using specialized transducers mounted around the circumference of the pipe. These waves travel along the length of the pipeline and reflect when they encounter changes in geometry or material condition, such as corrosion, wall thinning, cracks, or other structural anomalies. By analyzing the reflected signals, inspectors can identify and estimate the location of potential defects without the need to access the entire pipeline surface.



Guided wave testing is particularly useful for inspecting pipelines in areas that are difficult to access, such as sections buried underground, pipes passing through walls, or pipelines located under insulation or supports. In terminal facilities, this technique is often applied as a screening tool to quickly assess long pipe segments and identify areas that may require more detailed inspection using other non-destructive testing methods. While guided wave testing does not typically provide the same level of precise defect sizing as some other techniques, it offers significant advantages in terms of speed, coverage distance, and reduced need for extensive excavation or insulation removal.

### 3. Corrosion Monitoring and Prevention

Because corrosion is one of the most significant threats to pipeline integrity, effective corrosion control programs are essential. Corrosion gradually reduces pipe wall thickness and may eventually lead to leaks, ruptures, and serious safety or environmental incidents if it is not properly monitored and controlled. To effectively manage corrosion, operators implement corrosion monitoring programs that combine several techniques. These may include periodic ultrasonic thickness measurements, corrosion coupons, electrical resistance probes, and smart pigging inspections where applicable. Regular monitoring allows engineers to track corrosion rates and identify areas where wall loss is occurring before the integrity of the pipeline is compromised.



Ultrasonic Thickness Measurement

Preventive measures are equally important. Proper material selection, protective coatings, and cathodic protection systems are widely used to prevent external corrosion. For internal corrosion control, operators may apply corrosion inhibitors, remove water from the system, or improve filtration to reduce contaminants. Maintaining proper operating conditions and performing routine inspections are also key elements of a comprehensive corrosion management strategy.

### 3.1 Protective Coatings

Protective coatings act as a barrier between the metal surface and the environment. Properly applied coatings significantly reduce the rate of external corrosion.



Holiday Test and Paint thickness Measurement

However, coatings may degrade over time due to environmental exposure, mechanical damage, or improper application. Regular inspection is therefore necessary to identify coating defects.

### 3.2 Cathodic Protection

Cathodic protection is a critical method for preventing corrosion on pipelines by applying a controlled electrical current that counteracts the natural electrochemical reactions responsible for metal degradation. This technique effectively shifts the pipeline to a cathodic state, reducing or halting the corrosion process.

Two primary types of cathodic protection systems are commonly employed: sacrificial anode systems, which use more reactive metals to corrode in place of the pipeline, and impressed current systems, which rely on an external power source to provide a continuous protective current. Cathodic protection is especially vital for buried pipelines and those exposed to highly corrosive environments, such as soils with high moisture or aggressive chemical content, where the risk of external corrosion is significant.

#### 4. Risk-Based Inspection (RBI)

Risk-Based Inspection (RBI) represents a modern approach to pipeline integrity management, moving beyond traditional fixed-interval inspection programs by prioritizing inspections based on risk. RBI involves evaluating both the probability of failure and the potential consequences for each pipeline segment, allowing inspection and maintenance efforts to focus on areas that pose the highest risk to safety, the environment, and operational continuity. Key factors considered in an RBI assessment include operating conditions such as pressure and temperature, the type of product being transported, historical corrosion or damage data, pipeline age, environmental sensitivity, proximity to populated or critical areas, and the operational importance of the pipeline segment. By integrating these factors, RBI enables terminal operators to optimize inspection intervals, allocate resources more efficiently, and proactively address potential integrity issues before they result in failures. This data-driven approach enhances safety, reduces unplanned downtime, and supports cost-effective maintenance planning.

#### 5. CONCLUSION

Pipeline inspection is a critical element of safe and reliable operations in oil and gas terminals. Because pipelines transport large volumes of flammable hydrocarbons under pressure, even minor defects can lead to significant safety and environmental risks if left undetected.

A comprehensive pipeline integrity program should include regular visual inspections, NDT techniques, corrosion monitoring, and risk-based inspection methodologies. Combining these approaches allows terminal operators to detect early signs of degradation and implement timely maintenance actions.

*In modern oil and gas terminals, digital inspection management systems and advanced diagnostic tools are further enhancing the ability of engineers to monitor pipeline condition and predict potential failures. Through systematic inspection and proactive integrity management, operators can extend pipeline service life, protect personnel and the environment, and ensure the uninterrupted transfer of hydrocarbon products.*

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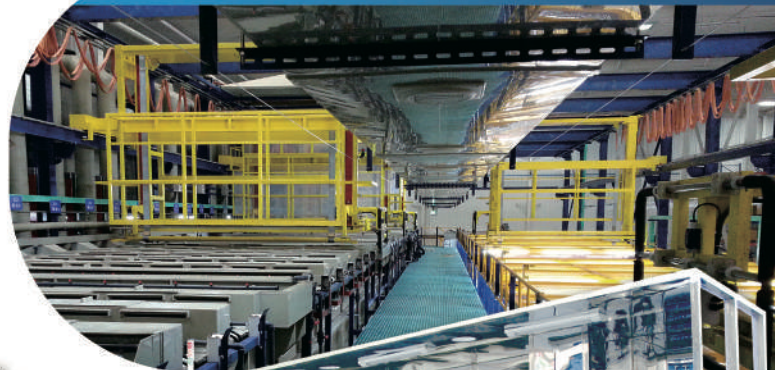
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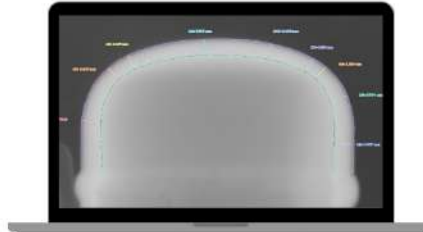
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How digital measurement standardization addresses the hidden cost of operator variability in radiographic wall thickness profiling?

## About MasterAIM™

MasterAIM is a digital measurement platform developed by MasterAIR Technologies Pte Ltd, Singapore, for the analysis of digitized conventional radiographic films. For more information, visit [masterair.ai/ai-automation/masteraim](http://masterair.ai/ai-automation/masteraim)

*This application note is based on findings from a study pending submission for a peer-reviewed journal publication. Full statistical methodology and results will be available in the accompanying publication.*

### The Measurement That Matters Most

In every petrochemical refinery, power plant, and offshore platform, a single number drives some of the most consequential engineering decisions: the remaining wall thickness of a pipe. That number determines whether a line stays in service, gets scheduled for repair, or triggers an emergency shutdown. It underpins fitness-for-service assessments, informs risk-based inspection strategies, and ultimately protects both people and assets.

For decades, the industry has relied on skilled radiographic interpreters to extract that number from conventional film. The process is well-established: expose the pipe, develop the film, place it on a light box, measure with a ruler and calipers, correct for magnification, and report the result. It works. It has kept plants running safely for generations. But here is a question that is rarely asked out loud: if you gave the same film to three qualified interpreters, would they give you the same answer?

### Three Operators, One Film, Different Answers

A recent independent study set out to answer exactly that question.

Three qualified radiographic interpretation operators were given 28 carbon steel pipe segments, yielding 84 distinct measurement locations, and asked to measure wall thickness three times each, using both traditional manual tools and a digital measurement platform (MasterAIM). That is 756 individual measurements per method, designed to quantify not just whether the measurements are accurate, but whether they are *consistent*. The study applied Gage Repeatability and Reproducibility (Gage R&R) analysis, a formal statistical framework widely used in manufacturing quality control but rarely applied in NDT, to decompose measurement variability into its component sources. The results revealed a clear picture. When the same operator measured the same location repeatedly, both methods performed well. **Repeatability was comparable: approximately 8-9% of total variation for both digital and traditional methods.** The individual operator's hand is steady. The expert's precision is real.

The divergence appeared when *different* operators measured the same location. **Reproducibility, which is the variation between operators, accounted for 19.31% of total variation in the traditional method, compared with 6.07% in the digital method.** That is a threefold difference. In practical terms, it means that the answer you get depends, in part, on who reads the film.

## Why Skilled Operators Disagree

This is not a question of competence. The operators in this study were qualified, experienced professionals. The variability arises from a fundamental limitation of manual radiographic interpretation: ambiguous visual features are interpreted differently by different people. Two steps in the measurement workflow are particularly susceptible. The first is calibration, establishing the pixel-to-millimeter (or on-film-to-real-world) conversion ratio using a reference object, typically a 25.4 mm steel sphere. In the traditional method, the operator measures the projected sphere diameter with a ruler.

Critically, this variability is not simply an equipment offset that could be corrected by standardizing the display. When the study removed each operator's systematic baseline difference, the operator-specific interaction, which is the pattern of which images each operator found difficult, remained substantial at 37.63% of total variation. Operators do not just disagree by a constant amount; they disagree differently on different images.

The second susceptible step is wall edge identification.

Determining where the inner and outer wall boundaries lie within the blurred transition zone of the radiographic image. This is an inherently subjective judgement call. One operator's "midpoint" is another operator's "slightly inside." The cumulative effect of these two interpretive steps, calibration and edge identification, produces the reproducibility gap observed in the study.

Post-study feedback from one of the operators confirmed these findings. The operator identified three categories of variability in their own traditional calibration measurements: outright measurement mistakes, ambiguous sphere geometry where the measured value depended on which reference points were selected, and unexplained trial-to-trial drift. On the ambiguous geometry, the operator noted: **"Both values are valid based on the selected edges."**

This single statement captures the core of the problem. When two equally valid interpretations of the same feature produce different numbers, the measurement system has introduced uncertainty that no amount of operator training can fully eliminate.

## What This Means for the Inspection Vendor

For inspection companies, measurement variability is a reputational and operational risk. If two operators from the same company produce materially different wall thickness reports on the same pipe, the client has reason to question the reliability of the service. Disputes arise, re-inspections are requested, and confidence erodes.

The study quantified this using the Intraclass Correlation Coefficient (ICC), a single metric that captures overall measurement system reliability on a scale from 0 to 1. The digital method achieved an ICC of 0.85, compared with 0.72 for the traditional method. In practical terms, 85% of the variation in digital measurements reflects true differences between pipes, while only 72% does so for traditional methods. The remaining variation is measurement noise. Noise that the inspection vendor's client is paying for but receiving no value from.

A digital measurement platform addresses this directly. Standardizing how calibration is performed and how wall boundaries are identified, it reduces the operator-dependent component of the measurement. The result is that different operators within the same company produce more consistent reports, building client confidence and reducing the cost of rework and dispute resolution.

## What This Means for the Asset Owner

For the plant operator or asset owner, measurement variability translates directly into decision-making uncertainty. The remaining wall thickness is compared against a minimum required thickness, and the difference constitutes the available safety margin. Any measurement uncertainty consumed by the measurement system reduces the effective margin available for engineering judgement. Consider a practical example. A pipe has a true remaining wall thickness of 3.0 mm and the minimum required thickness is 2.0 mm, leaving a safety margin of 1.0 mm. If the measurement system has a precision of 0.5 mm, then measurement uncertainty alone accounts for 50% of the available safety margin. The asset owner is making a run-or-replace decision with only half of the margin they think they have. Reducing the measurement system's variability from 0.5 mm to 0.25 mm effectively doubles the usable safety margin without changing the physical condition of the pipe.

The consequences of this uncertainty flow in both directions. An optimistic measurement may delay necessary maintenance, increasing the risk of in-service failure. A conservative measurement may trigger premature replacement of serviceable pipe, incurring unnecessary capital expenditure and operational downtime. In either case, the asset owner is paying a price for measurement noise that a more reliable system could reduce.

### How Digital Standardization Addresses Both

The MasterAIM digital measurement platform applies software-based measurement tools to digitized conventional radiographic films. Rather than replacing the film acquisition workflow, it replaces the interpretation layer, the calibration and wall edge identification steps, where the majority of operator-dependent variability originates. The study demonstrated that this approach preserves the repeatability of skilled manual interpretation (both methods at ~8-9%) while reducing reproducibility variation by a factor of three (6.07% vs. 19.31%).

Beyond the statistics, a digital measurement environment provides something that manual interpretation fundamentally cannot: a complete, auditable record of how every measurement was made. When a measurement is performed, the digitized image, the calibration parameters, the edge detection results, and the final wall thickness value are all captured and stored together. If a measurement is ever questioned, by a client, a regulator, or a future inspector revisiting the same pipe years later, the entire measurement process can be reconstructed and reviewed.

With traditional manual measurement, the only record is the number written on a report. If that number is disputed, there is no way to determine how the operator arrived at it, where they placed the ruler, how they identified the wall edges, or which part of the calibration sphere they measured. The measurement is a black box. A digital system turns that black box into a transparent, reviewable, and defensible process.

A digital measurement platform also transforms the relationship between the inspection vendor and the asset owner. Traditionally, the asset owner receives a report containing final wall thickness values with no visibility into how those numbers were derived. If the asset owner questions a result or commissions a second opinion, the re-inspection starts from scratch, with a different operator, potentially a different interpretation, and no basis for reconciling the two. When both parties operate on a shared digital platform, the measurement becomes a conversation rather than a handoff. The vendor can present not just the result but the digitized image, the calibration parameters, and the edge detection overlay alongside it. The asset owner or their independent reviewer can open the same file, verify the measurement methodology, and if necessary, re-measure the same image using the same tools. Discrepancies become traceable to specific interpretive decisions rather than opaque disagreements between competing numbers. This shared visibility reduces the adversarial dynamic that often accompanies measurement disputes and creates a collaborative framework for decision-making.

There is a further, often overlooked advantage to this approach. High-quality conventional radiographic film captures spatial detail at a resolution that can exceed that of many digital detector arrays. When these films are digitized at high resolution, the resulting digital image contains information that was always present in the film but was inaccessible to manual interpretation. Subtle density gradients, fine edge profiles, and sub-millimeter features that a ruler on a light box simply cannot resolve. Digital measurement tools can access and analyze this latent information, extracting more from existing films than was previously possible. For the inspection vendor, this means the ability to demonstrate the basis of every reported value, protecting against disputes and supporting quality management systems. For the asset owner, it means confidence that the numbers driving their integrity decisions are traceable, reproducible, and grounded in a standardized methodology rather than individual operator judgement.

### Looking Ahead

*The findings of this study represent a first step in the formal validation of digital measurement tools for conventional radiographic films. While digital radiography continues to gain adoption, conventional film remains a mainstay in most inspection workflows and the existing archive of historical films represents a vast, largely untapped resource. Adopting a digitized interpretation workflow allows operators to extract greater value from these existing assets while integrating conventional data into modern digital pipelines, bridging the gap between legacy practice and the digital future of asset integrity management.*



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ISO9712 Scheme-testing- Qualification and certification of NDT personnel .

### -4 ISO 17020:2012 Conformity assessment for inspection body

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# The True Cost of Late Detection:

## Why In-Process NDT is Needed for Composite Manufacturing

By Professor Bryn C. Hughes, Chief Scientist for NDT, Adaptix



Bryn C. Hughes

Across every industry adopting advanced composite components - such as *automotive, aerospace, renewable energy, and medtech* - the dominant inspection model currently places quality assessment at the very end of the process, precisely when the cost of failure is greatest. By the time a defect is detected at the end of the manufacturing line, the full cost of producing that part has already been incurred. Energy, materials, labor and machine time have all been spent. What typically follows is either an expensive rework cycle or scrap - both of which erode margin and extend lead times. With components growing in size and complexity across multiple industries, tolerance for that level of waste is narrowing fast. It is important to remember that the economics of defect detection are not linear. A flaw identified during lay-up might cost relatively little to address; the same defect found after cure or at sub-assembly could cost orders of magnitude more to resolve, even where resolution is possible.

The consequences vary by sector, but the underlying economics do not.

*In automotive production, a defective structural composite part identified late in the build sequence disrupts line flow and can lead to costly retooling. In renewable energy, a wind turbine blade found to contain internal delamination after curing may mean a full re-spin of a manufacturing process that has taken days. In marine applications, structural composites that fail inspection after lamination may have to be scrapped entirely. In medtech, late detection can mean high-volume production of non-conforming parts before the problem is caught. In aerospace, delayed discovery extends program timelines and adds pressure to already strained supply chains.*

Historically, in-process inspection has been impractical due to the limitations of existing imaging technologies in live production environments.

Ultrasonic testing (UT) is widely used and effective at detecting delamination and porosity, but contact-based methods require careful surface coupling and can be slow on large or geometrically complex parts. Phased-array UT demands skilled operators and significant scan time.

Thermography and shearography offer rapid, non-contact coverage of large surface areas and are well suited to near-surface defect detection, but their sensitivity diminishes with depth, limiting effectiveness on thicker laminates. Conventional X-ray CT delivers the most complete 3D characterization of internal defects, but the time required to acquire and process a full tomographic dataset - and the facility infrastructure involved - make it impractical for most in-process monitoring. As a result, for most components, parts have to travel to specialist inspection facilities, adding time and cost to the process while entrenching a quality model built around late discovery and expensive correction.



Low-power digital tomosynthesis - an approach that sits between conventional 2D X-ray and full CT - takes a series of images from multiple positions and algorithmically reconstructs them to provide cross-sectional slices through a part. The radiation doses involved are a fraction of those associated with conventional CT, significantly reducing the shielding and exclusion zones that have traditionally made X-ray technology difficult to deploy outside of dedicated facilities.

The result is meaningful 3D structural data delivered in a fraction of the time of CT, using equipment compact and flexible enough to be deployed directly on the shop floor. For smaller suppliers and contract manufacturers, this opens up in-house inspection capability that was previously out of reach.

Critically, this technology can be applied to large components and complex geometries that are incompatible with CT.

Porosity, delamination, fiber misalignment and other critical defects can now be detected at lay-up, pre-cure, or sub-assembly stages

- precisely the points at which intervention is still viable and correction, rather than scrapping, remains cost-effective. This means that components such as fuselage panels, wing structures and propeller blades can be inspected on the shop floor, without the handling risk or production delays associated with transporting parts to a centralized or off-site facility.

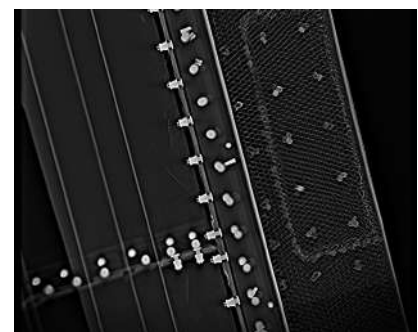
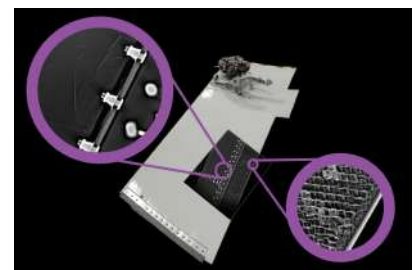
This same portability, which adds value during the manufacturing process, also extends to testing components in service.

For MRO operations, the ability to conduct high-quality imaging of a component on the ground - without moving it or transporting it to an off-site facility - is a real step forward in inspection efficiency. A system deployed in an aerospace hangar, for example, with a modest safety perimeter in place, can assess composite control surfaces or fairings in situ, with findings available in near real time.

Additionally, where in-process inspection data is mapped to a component's 3D model at the point of manufacture,

-that data travels with the part. MRO teams examining a component years later can reference the original build record to understand how the structure was made, what anomalies were present from the outset, and how it has changed in service. For automotive industries, that same data can inform warranty analysis and design iterations, while in medtech, it may underpin the device history record.

Crucially, it creates a feedback loop between manufacturing quality and product design that makes the entire process more intelligent over time. Earlier-stage NDT enables a fundamental shift in how quality is built into the manufacturing process, moving from inspection as validation to inspection as control: Scrap rates can be reduced; rework cycles shortened; production flows maintained; and lead times reduced. The data generated can also be fed directly back into process optimization, helping manufacturers identify and address systemic issues before they become embedded in production.



There are real sustainability benefits to this approach too. Reducing scrap means reducing wasted material - a factor growing in importance as composite structures become larger, more technically complex, and more resource-intensive to produce. While composites offer a proven way to lightweight components, they are energy-intensive to make and difficult to recycle so, in a world of interlinked net zero reporting, reducing preventable manufacturing waste is not merely good practice but strategically important. As the industry works toward net zero targets, the ability to eliminate avoidable waste at the point of production matters both economically and environmentally.

Manufacturers who invest in in-process NDT can not only gain an operational edge - such as lower scrap costs, increased throughput, stronger quality data, and greater supply chain resilience - but, as composite components become more common and quality expectations rise, in-process inspection will evolve from a market differentiator to a baseline expectation.

The question is not whether to invest, but whether to do so before or after your competitors?



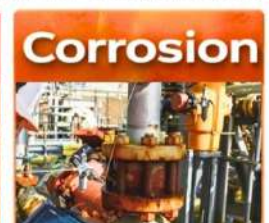
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# Advanced PAUT Ecosystems for Smarter T&I Execution and Precision-Driven Integrity Management



Mohamed Abufour

Turnaround and Inspection (T&I) operations represent one of the most operationally sensitive and strategically significant phases in the lifecycle management of oil and gas assets. These planned shutdowns are executed within highly compressed schedules where inspection performance directly influences safety assurance, regulatory compliance, production continuity, operational reliability, and long-term asset integrity. As industrial infrastructure becomes increasingly complex and maintenance windows continue to narrow, conventional inspection methodologies often struggle to deliver the speed, precision, traceability, and data confidence demanded by modern integrity management frameworks.

Advanced Phased Array Ultrasonic Testing (APAUT) technologies are redefining turnaround execution by integrating high performance instrumentation, advanced 128:128 architecture, intelligent software ecosystems, specialized probes and encoded scanners,

cloud enabled collaboration, real-time data synchronization, and analytics driven inspection workflows within a unified digital inspection environment. This integrated approach significantly enhances inspection productivity, accelerates engineering decision making, improves defect characterization accuracy, and strengthens data integrity, enabling smarter, faster, and more reliable turnaround execution.

## The Growing Demands of Modern T&I Operations

Within the Oil and Gas Sector, T&I operations directly influence operational continuity, safety performance, asset availability, and long-term reliability. Unlike routine maintenance activities, turnarounds are executed during tightly constrained shutdown intervals where every inspection activity impacts restoration schedules, maintenance coordination, and restart readiness. Every additional hour of shutdown can result in substantial production losses, increased operational expenditure, and significant downstream economic impact.

Consequently, inspection has evolved from a supporting maintenance function into a strategic operational discipline responsible for delivering accurate, traceable, high confidence integrity data under severe schedule pressure.

Inspection outcomes ultimately determine whether critical assets can safely return to service, require repair, undergo replacement, or demand further engineering evaluation. Weld integrity assessment, corrosion mapping, crack detection, and piping condition evaluation therefore become decisive factors in restart authorization, maintenance prioritization, and risk mitigation planning. However, aging infrastructure, increasingly complex process facilities, harsher operating conditions, and elevated reliability expectations have exposed the limitations of many conventional Non-destructive Testing workflows. Traditional inspection methodologies frequently encounter challenges associated with restricted productivity, delayed reporting, inconsistent acquisition quality, fragmented data management, and limited real-time engineering visibility.

To address these operational challenges, advanced PAUT technologies integrated within intelligent digital inspection ecosystems are transforming how inspection supports turnaround execution, integrity assurance, and reliability centered asset management.



### Inspection as a Strategic Driver of Turnaround Performance

Inspection activities during T&I operations are designed to identify, characterize, and quantify degradation mechanisms that may compromise operational safety, equipment reliability, and structural integrity. Typical applications include weld inspection for fabrication quality assessment and in-service degradation analysis, corrosion mapping for wall thickness evaluation and material loss characterization, crack detection for fatigue related and stress induced discontinuities, and piping integrity assessment for localized thinning, erosion, and base metal degradation.

The reliability and accuracy of these inspections directly influence engineering decisions associated with fitness-for-service evaluations, repair prioritization, remaining-life assessment, risk mitigation,

and restart authorization. In high consequence industrial environments, uncertainty in inspection data can result in overly conservative maintenance decisions, unnecessary component replacement, prolonged shutdown duration, and increased operational expenditure. Conversely, high fidelity inspection data empowers integrity engineers to make precise, technically defensible, and risk informed decisions with greater confidence and operational clarity.

Modern T&I operations therefore require inspection systems capable of delivering high resolution defect characterization, full volumetric inspection coverage, accelerated inspection throughput, real-time engineering visibility, reliable and traceable data acquisition, advanced imaging capability, integrated digital workflow management, and enhanced inspection repeatability. The operational challenge is no longer limited to inspection execution alone; it now centers on execution efficiency, inspection intelligence, data accessibility, and operational responsiveness under severe schedule constraints.

### Why Conventional Inspection Workflows Fall Short

Despite advancements in Non-destructive Testing technologies, many turnaround operations continue to rely on fragmented workflows and legacy inspection systems that restrict operational efficiency and compromise data

continuity. One of the most significant limitations is reduced inspection productivity during compressed shutdown schedules. Manual scanning methodologies and slower acquisition rates frequently constrain inspection throughput, creating operational bottlenecks that delay engineering evaluations, repair planning, and restoration activities.

Data consistency and reporting reliability also remain critical concerns. Incomplete inspection coverage, inconsistent acquisition quality, fragmented reporting structures, and limited traceability can reduce confidence in inspection outcomes and complicate integrity assessments. Another major challenge involves disconnected communication between field inspection personnel and integrity engineering teams. Conventional workflows often rely on sequential reporting processes in which inspection data is transferred and reviewed only after field execution progresses. This delay limits real-time engineering decision making, slows repair validation, and extends restoration timelines. Additionally, many conventional inspection platforms struggle with adaptability, scanning efficiency, environmental robustness, and workflow integration in demanding industrial environments. These limitations create a widening gap between inspection capability and the operational performance requirements of modern turnaround execution.

## Advanced PAUT: A Smarter Approach to Inspection

Phased Array Ultrasonic Testing has emerged as one of the most advanced and operationally effective ultrasonic inspection technologies for addressing the increasingly complex demands of modern T&I operations. Unlike conventional ultrasonic testing methods, PAUT enables electronic beam steering, dynamic focusing, and multi-angle scanning through the controlled activation of multiple transducer elements. This advanced capability delivers enhanced defect detection sensitivity, improved characterization of flaw orientation and geometry, full volumetric inspection coverage, increased probability of detection, faster scanning performance, superior imaging resolution, improved inspection repeatability, and enhanced data acquisition consistency. The value of advanced PAUT increases substantially when integrated within a connected inspection ecosystem that combines high-performance instrumentation, intelligent software architecture, specialized phased array probes, encoded scanners, cloud-enabled collaboration, and advanced workflow management capabilities.



This technological evolution represents a strategic shift from isolated inspection tools toward intelligent inspection ecosystems capable of supporting high-efficiency turnaround execution, predictive maintenance strategies, and precision-driven integrity management.

## Connected Inspection Ecosystems for Modern Turnarounds

Modern PAUT ecosystems are specifically engineered to meet the operational demands of complex turnaround environments where speed, reliability, precision, and data accessibility are mission critical. At the core of these advanced systems is a high performance 128:128 PAUT architecture capable of delivering exceptionally high-resolution volumetric inspection coverage across complex geometries and critical inspection zones. High channel configurations significantly enhance imaging performance, improve defect characterization accuracy, strengthen signal clarity, and support reliable inspection execution under demanding field conditions.

These systems are further strengthened through the integration of advanced digital capabilities, including cloud-based software infrastructure for centralized inspection management, real-time data synchronization, remote collaboration, intelligent workflow automation, advanced analytical software, and seamless integration between acquisition, analysis, and reporting environments. The inspection ecosystem is also supported by a comprehensive portfolio of advanced inspection accessories and scanning solutions, including specialized phased array probes for weld inspection, corrosion mapping, and crack detection; encoded scanners for precise positional tracking and repeatable inspection performance; corrosion mapping scanners for rapid large area coverage; and automated or semi-automated scanning solutions for improved acquisition consistency and productivity.

Together, these technologies significantly increase inspection throughput while reducing operator dependency, minimizing acquisition variability, and strengthening overall data reliability. Beyond hardware capability, integrated digital platforms enhance workflow coordination and engineering collaboration by enabling centralized inspection planning, real-time communication between inspectors and integrity engineers, immediate review and interpretation of inspection data, structured data management with cloud-enabled accessibility, and advanced analytics for faster engineering response and repair validation.



## Operational Impact on T&I Execution

The integration of advanced PAUT technologies within connected inspection ecosystems delivers measurable operational improvements across every phase of turnaround execution. Real-time accessibility of inspection data significantly reduces delays associated with traditional reporting workflows. Integrity engineers can evaluate inspection outcomes immediately, enabling faster repair validation, shorter engineering response cycles, improved maintenance coordination, and accelerated return-to-service execution.

High-resolution imaging capability and advanced acquisition performance substantially improve the characterization of weld defects, corrosion mechanisms, crack morphology, and material degradation. Enhanced sizing accuracy, superior signal clarity, and advanced analytical functionality strengthen confidence in engineering assessments and reduce uncertainty during fitness-for-service evaluations.

Accelerated scanning performance, intelligent workflow optimization, and automated acquisition capability improve inspection throughput during highly constrained shutdown schedules. This enables more efficient deployment of inspection resources while reducing operational bottlenecks during critical turnaround phases. Connected digital inspection environments also improve communication between field personnel, integrity engineers, and maintenance planners, enabling immediate technical review, faster decision making, and more agile operational response during critical maintenance activities.

Reliable volumetric inspection data further supports more accurate condition assessment, degradation monitoring, and risk informed maintenance planning. Operators can optimize maintenance intervals, reduce unnecessary shutdown frequency, minimize operational disruption, and maintain integrity assurance while improving overall operational efficiency.

## Strategic Value Beyond Inspection

Beyond immediate operational improvements, intelligent PAUT ecosystems deliver substantial long-term value to integrity management programs and broader business performance objectives. Reduced turnaround duration improves production availability, minimizes shutdown related losses, and enhances operational profitability. Improved inspection productivity supports more efficient utilization of technical resources, while enhanced data quality strengthens maintenance planning, reliability engineering, and lifecycle management strategies.

Integrated inspection intelligence also improves alignment between inspection execution and enterprise integrity programs by supporting risk-based maintenance planning, data driven integrity assessments, long-term degradation monitoring, improved regulatory traceability, reliability centered maintenance strategies, predictive maintenance initiatives, and enhanced asset lifecycle optimization. As inspection data becomes increasingly integrated into operational decision-making frameworks, inspection evolves beyond a compliance-driven activity into a strategic contributor to asset performance optimization, operational resilience, and industrial reliability management.



# STRATEGIC VALUE BEYOND INSPECTION

Beyond immediate operational improvements, intelligent PAUT ecosystems deliver substantial long-term value to integrity management programs and broader business performance objectives.

 <p><b>STRENGTHEN INTEGRITY</b></p> <ul style="list-style-type: none"> <li>Detect earlier.</li> <li>Understand deeper.</li> <li>Reduce risk.</li> </ul>	 <p><b>OPTIMIZE PERFORMANCE</b></p> <ul style="list-style-type: none"> <li>Smarter decisions.</li> <li>Fewer disruptions.</li> <li>Higher efficiency.</li> </ul>	 <p><b>DRIVE VALUE</b></p> <ul style="list-style-type: none"> <li>Lower total cost.</li> <li>Extend asset life.</li> <li>Maximize return.</li> </ul>	 <p><b>EMPOWER PEOPLE</b></p> <ul style="list-style-type: none"> <li>Better insights.</li> <li>Stronger teams.</li> <li>Confident decisions.</li> </ul>	 <p><b>BUILD A SUSTAINABLE FUTURE</b></p> <ul style="list-style-type: none"> <li>Safer operations.</li> <li>Lower emissions.</li> <li>Responsible growth.</li> </ul>
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## CONCLUSION

Modern Turnaround and Inspection operations demand far more than conventional inspection instrumentation. They require intelligent, fully connected inspection ecosystems capable of delivering high-resolution data, accelerated execution, operational reliability, real-time engineering visibility, and advanced analytical capability under severe schedule constraints.

Advanced PAUT technologies combined with high-performance 128:128 architecture, specialized scanning solutions, cloud-enabled collaboration, intelligent workflow platforms, and integrated inspection analytics represent a major advancement in inspection execution and integrity management.

Through improved inspection productivity, enhanced data confidence, accelerated engineering decision-making, superior defect characterization precision, and seamless digital collaboration, connected PAUT ecosystems enable a more efficient, intelligent, and strategically aligned approach to asset integrity management.

As industrial assets continue to increase in complexity and turnaround windows become progressively narrower, intelligent inspection ecosystems will play an increasingly critical role in supporting operational reliability, safety assurance, production continuity, regulatory compliance, and long-term asset performance optimization.

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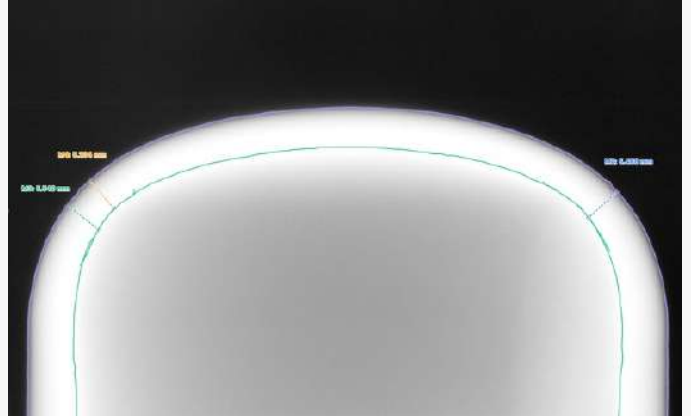
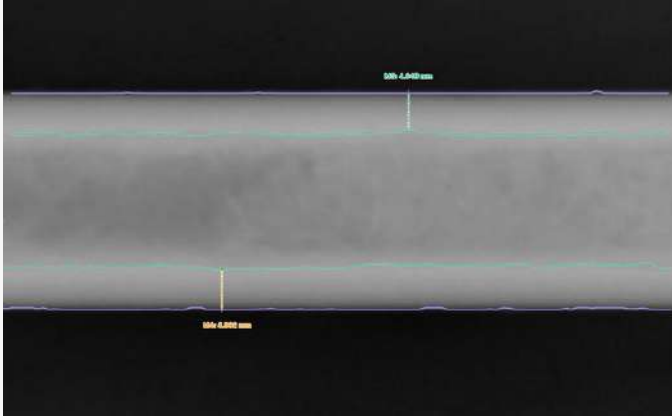
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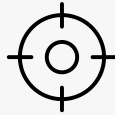
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# NDT CASE STUDY of the Quarter

## Turbine Engine

Engine Specs:

- Narrow internal passages
- Complex blade geometries.

## Camera Details

Model: RVI Inspector Plus  
 Probe Dia.: 2.8 mm — 1.0 mm



## Remote Visual Inspection

### Aircraft Engine Inspection with Ultra-Thin Industrial Videoscope

#### INTRODUCTION

Aircraft engine inspection is one of the most demanding applications in remote visual inspection (RVI). Modern turbine engines contain extremely narrow internal passages, complex blade geometries, and sensitive components that require regular inspection without unnecessary disassembly.

In many situations, inspectors must access areas with limited entry diameters while maintaining sufficient image quality and maneuverability. This is where ultra-thin industrial videoscopes have become increasingly important.

Today, probe diameters below 2.8 mm — and even below 1.0 mm — are expanding the possibilities of non-destructive inspection in aerospace maintenance and manufacturing environments.

#### The Challenge of Aircraft Engine Inspection

Aircraft engines operate under extreme thermal and mechanical stress. During maintenance inspections, technicians commonly look for:

- ✓ Cracks
- ✓ Foreign object damage (FOD)
- ✓ Blade deformation
- ✓ Carbon deposits
- ✓ Coating deterioration
- ✓ Cooling hole blockage
- ✓ Corrosion and wear

However, many modern engines offer only very limited access points. Traditional larger-diameter videoscopes may not fit into cooling channels, guide vane gaps, or internal cavities. At the same time, inspectors still require:

- Stable image quality
- Flexible articulation
- Reliable illumination
- Accurate navigation inside complex geometries

Balancing miniaturization and inspection performance remains one of the key technical challenges in aerospace RVI.



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## Why Ultra-Thin Videoscopes Matter

Ultra-thin videoscopes allow inspectors to enter previously inaccessible areas without removing additional components from the engine.

Typical applications include:

- Turbine blade inspection
- Combustion chamber inspection
- Cooling hole examination
- Fuel nozzle inspection
- Internal cavity inspection
- Narrow passage verification

Probe diameters between 0.95 mm and 2.8 mm are increasingly used where conventional 4 mm or 6 mm systems are too large.

In practical aerospace maintenance, reducing disassembly directly reduces downtime and maintenance cost.

## The Difference Between Fiberscope and Videoscope

Traditionally, ultra-small inspections were performed using optical fiberscopes. While fiberscopes remain useful in certain applications, modern ultra-thin videoscopes provide several advantages:

### Improved Digital Imaging

Digital CMOS imaging enables image capture, recording, and documentation.

### Better Reporting Capability

Inspection images and videos can be stored for maintenance records and quality documentation.

### Easier Training and Collaboration

Live image display allows multiple technicians to review inspection results simultaneously.

## Enhanced Workflow

Portable touchscreen systems improve navigation, file management, and reporting efficiency.

As digital imaging technology continues to improve, ultra-thin videoscopes are increasingly replacing traditional fiberscopes in many industrial applications.

## Practical Limitations of Ultra-Thin Probes

Although ultra-thin videoscopes provide major advantages, there are also engineering limitations.

Miniaturization creates challenges such as:

- Lower light output
- Reduced articulation space
- Limited sensor size
- Increased fragility
- Higher repair complexity

For probes below 1.2 mm, even small mechanical impacts can damage internal optical fibers or articulation structures.

Therefore, successful use of ultra-thin videoscopes requires careful handling and realistic expectations regarding durability and repair cost.

## Selecting the Right Probe Diameter

Choosing the correct probe diameter depends on balancing accessibility and image quality.

**0.95 mm – 1.2 mm:** Suitable for extremely restricted access areas where entry size is the primary limitation.

**1.8 mm – 2.8 mm:** Often considered the best balance between flexibility, durability, and inspection performance.

**4 mm – 6 mm:** Preferred for general turbine inspection where higher image resolution and stronger articulation are required.

In many aerospace inspections, combining multiple probe diameters provides the most practical solution.

## Future Trends

The aerospace inspection industry continues to push toward:

- Smaller probe diameters
- Higher image resolution
- Better articulation systems
- Dual-camera technology
- Improved portability
- AI-assisted defect recognition

However, practical usability and reliability remain more important than excessive feature complexity.

For many maintenance teams, inspection efficiency, durability, and serviceability are still the most critical factors in daily operation.

## Conclusion

Ultra-thin industrial videoscopes are transforming aircraft engine inspection by enabling access to previously unreachable internal areas while reducing disassembly requirements. As aerospace maintenance demands continue to evolve, the balance between miniaturization, image quality, and practical reliability will remain a key focus for the RVI industry.

*The future of aircraft engine inspection is not only about smaller probes — but also about smarter, more practical inspection solutions.*

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