



The Robotics Journey

working at heights

January 2026

human energy[®]



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working at heights

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Robotics for working at heights and in confined spaces is moving from pilots to everyday practice. The driver is clear: keep people out of harm's way while improving the quality, speed, and traceability of inspection and maintenance. Documented deployments show meaningful reductions in exposure and turnaround impact, with data that is denser and more repeatable than manual spot checks. At the same time, standards and procedures are evolving so that robotic outputs can support risk based inspection and fitness for service decisions. The opportunity is real, but adoption is not automatic. Success requires disciplined change management, site readiness, and a focus on the human side of the transition.

This article offers a practical path forward. We outline where robots and drones add the most value today, from visual inspection and nondestructive testing to targeted cleaning and coating. We highlight lessons learned from Chevron's Robotics program and our partners, reflecting field results across a range of assets and environments. Our intent is to help owners, service providers, developers, and standards bodies move from isolated trials to scaled, repeatable deployment. The goal is consistent: reduce exposure, raise reliability, and make better decisions with better data. With collaboration and disciplined execution, robotics becomes another tool for operational excellence, supporting safe, reliable, and ever cleaner energy.



THE HIGH-STAKES PROBLEM: WORK AT HEIGHTS IN THE ENERGY SECTOR

Work at heights in the energy sector isn't optional. For Chevron, ensuring these tasks are done safely and reliably has been a long-standing priority. Inspecting flare stacks, maintaining storage tanks, and keeping offshore platforms online and thousands of other tasks all require elevation work. Deferring these tasks accelerates asset degradation and increases the risk of catastrophic failure.

The underlying drivers are imperative and non-negotiable: stringent regulatory mandates from bodies like the Occupational Safety and Health Administration (OSHA) or the Bureau of Safety and Environmental Enforcement (BSEE) require proactive integrity management, while the physical laws of corrosion and fatigue demand constant vigilance.

The pattern of this work at heights is dictated by both predictable, pre-planned schedules and unforeseen events. It occurs during routine, multi-year inspection cycles,

planned maintenance turnarounds, or in urgent response to equipment failure or environmental damage. Historically, these tasks have been performed using conventional methods like scaffolding, ladders, and rope access, which inherently place personnel in high-risk environments of heights.

Understanding what needs to be done, why this work is essential, when it occurs, and how it is traditionally executed provides the critical context for evaluating new solutions.

This report will dive into the global statistics and operational realities that define this landscape, setting the stage for a new generation of technologies designed to make work at heights safer and more efficient.

If we
can't
reach it
safely,
we can't
run it
reliably

AGT (Above Ground Storage Tanks)

Key Activities: Visual Inspection, Ultrasonic Thickness (UT) Gauging, Weld Inspection
Frequency: 5 years (External); 10-20 years (Internal)
Relevant Standards: API 653, EPA SPCC

Elevated Piping

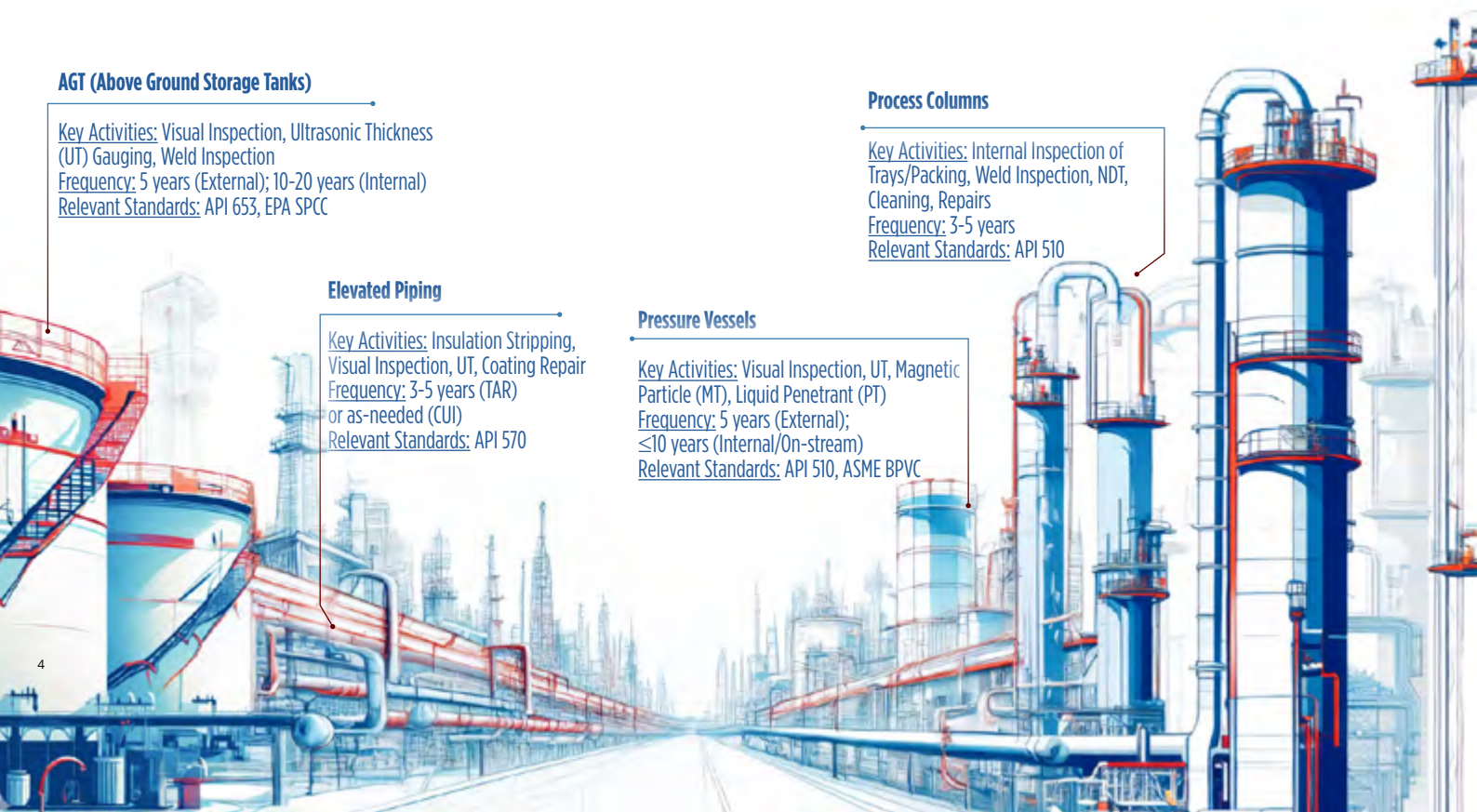
Key Activities: Insulation Stripping, Visual Inspection, UT, Coating Repair
Frequency: 3-5 years (TAR) or as-needed (CUI)
Relevant Standards: API 570

Process Columns

Key Activities: Internal Inspection of Trays/Packing, Weld Inspection, NDT, Cleaning, Repairs
Frequency: 3-5 years
Relevant Standards: API 510

Pressure Vessels

Key Activities: Visual Inspection, UT, Magnetic Particle (MT), Liquid Penetrant (PT)
Frequency: 5 years (External); ≤10 years (Internal/On-stream)
Relevant Standards: API 510, ASME BPVC



THE TRADITIONAL WAY

The choice of access method is a primary determinant of the direct cost, timeline, and safety profile of any work at heights project. The two dominant methods in industrial settings are traditional scaffolding and modern industrial rope access.



Scaffolding has long been the default solution for providing a stable work platform at height. However, it comes with significant logistical and financial burdens. The process involves substantial costs for the rental or purchase

of scaffolding components, transportation to the site, storage, and, most significantly, the extensive labor required for erection and dismantling. The setup and teardown process can take days or even weeks for complex structures. For heavy industrial applications, durable and high-load-capacity steel scaffolding is the standard, despite its higher initial cost and logistical challenges related to its weight. Furthermore, OSHA regulations require that any scaffold over 125 feet tall must have an engineered, stamped drawing¹.

Industrial rope access, governed by rigorous safety and training standards from organizations like the Industrial Rope Access Trade Association (IRATA) and the Society of Professional Rope Access Technicians (SPRAT), has emerged as a faster, more flexible, and highly cost-effective alternative for a wide range of tasks, particularly inspection and light maintenance. A key advantage is the speed of deployment; a rope access team can often rig their systems and begin work in under an hour,

compared to the days required for scaffolding. This method requires minimal equipment, uses smaller, highly-skilled crews, and avoids the costs associated with transporting and constructing a massive temporary structure.



This efficiency translates into direct project cost savings estimated to be between 30% and 70% compared to scaffolding². Of course, rope access can only be deployed for limited localized tasks. Tank cleaning or painting and other large scale tasks still require scaffolds.

WHAT THE INDUSTRY SPENDS ON ELEVATED WORK

AGT (Above ground storage tanks)³

Global installed fleet: 350,000
Work at Heights
Events per year: 93,300
Cost per Event: \$45,000
Estimated Annual Spend: \$4.2B



Elevated piping⁴

Global installed fleet: millions of miles
Work at Heights
Events per year: Tied to TARs
Cost per Event: variable
Estimated Annual Spend: \$9.5B



Pressure Vessels⁵

Global installed fleet: 22,000,000
Work at Heights
Events per year: 6,600,000
Cost per Event: \$3,500
Estimated Annual Spend: \$23.1B



Process Columns⁶

Global installed fleet: 400,000
Work at Heights
Events per year: 100,000
Cost per Event: \$70,000
Estimated Annual Spend: \$7B



The global fleet of large-scale industrial assets requiring significant work at heights is vast. This report concentrates on 4 big assets in that category. The analysis estimates an installed base of 350,000 large AGTs, over 22 million pressure vessels, and around 400,000 process columns globally. Elevated piping, while not quantifiable in units, represents millions of miles of infrastructure within the global refining and chemical production footprint.

Work-at-heights events are driven by a combination of prescriptive regulatory cycles,

planned operational shutdowns, and reactive, condition-based needs. Standards from the American Petroleum Institute (API 510, API 653), mandate external inspections every five years and more intensive internal inspections on cycles of ten years or more. Major plant turnarounds (TARs), occurring every three to five years, serve as the primary nexus for comprehensive work on columns and piping systems. Furthermore, pervasive issues like Corrosion Under Insulation (CUI) trigger a significant volume of unscheduled, high-urgency maintenance.

The primary cost drivers for operating and maintenance are not merely the direct expenses of access solutions like scaffolding or rope access, but the staggering opportunity cost of lost production. With facility downtime costs ranging from hundreds of thousands up to millions of dollars daily, there is a powerful economic incentive to adopt faster, safer, and more efficient inspection and maintenance technologies to avoid millions of hours of elevated work.

DECONSTRUCTING FAILURE & MEASURING RISK

What risk and safety means and how is it measured in the industry

Catastrophic incidents are rarely the product of a single error but the combination of systemic failures. At the core of this chain lies the most unpredictable variable: human factors. Fatigue, stress, and complacency contribute to nearly 90%⁷ of fall-related accidents, underscoring the limitations of administrative controls and Personal Protective Equipment (PPE) as primary barriers.

This creates a dangerous paradox. While safety equipment has incrementally improved, fatality rates remain stubbornly persistent, with recent data even showing an increase in fatal falls. The industry quantifies operational danger using a clear framework. Risk is fundamentally a product of two variables: the probability of an incident occurring and its severity (or impact). This calculation is visualized through the Risk Assessment Matrix, the standard decision-making tool for every operation on an industrial site. Any task plotting in the 'High' or 'Medium-High' risk categories mandates an immediate halt to operations until a mitigation strategy reduces the risk to an acceptable level.

For example, attempting to repair a flare stack via rope access while it is operational would place the 'Impact' at 'Catastrophic' and the

'Probability' as 'Likely', a clear high-risk scenario. The required mitigation is absolute: shut down the unit, thereby drastically reducing the probability of an incident.

Nowhere is this risk calculation more critical than at the intersection of the two most dan-

gerous industrial activities combined: working at height inside a confined space. In these environments, an incident can turn lethal quickly; a worker in an oxygen-deficient atmosphere can suffer brain damage or death in as little as four minutes. The danger is tragically compounded during rescue attempts. Data from the National Institute for Occupational Safety

RISK ASSESSMENT MATRIX

PROBABILITY	ALMOST CERTAIN	LOW MED	MEDIUM	MED HI	HIGH	HIGH
	LIKELY	LOW	LOW MED	MEDIUM	MED HI	HIGH
	POSSIBLE	LOW	LOW MED	MEDIUM	MED HI	MED HI
	UNLIKELY	LOW	LOW MED	LOW MED	MEDIUM	MED HI
	VERY UNLIKELY	LOW	LOW	LOW MED	MEDIUM	MEDIUM
		IMPACT				
		NEGLIGIBLE	MINOR	MODERATE	MAJOR	CATASTROPHIC

gerous industrial activities combined: working at height inside a confined space. In these environments, an incident can turn lethal quickly; a worker in an oxygen-deficient atmosphere can suffer brain damage or death in as little as four minutes. The danger is tragically compounded during rescue attempts. Data from the National Institute for Occupational Safety



EVOLUTION

from scaffolding to rope access to remote robotics work

While administrative procedures and Personal Protective Equipment (PPE) are essential, these measures only mitigate risk rather than eliminating the hazard. The first major evolution beyond cumbersome scaffolding was industrial rope access. With an exemplary safety record backed by governing bodies like IRATA, rope access proved that specialized training and techniques could make manual work at heights faster, more flexible, and significantly

safer than traditional methods. This evolution of manual practice sets the stage for the next logical step: deploying technology to remove the human from the hazard altogether. This transition is not happening all at once but through a spectrum of innovation.

Crawlers and manipulators are beginning to perform external and internal non-destructive testing on assets, acquiring high-quality data

without requiring scaffolding or hazardous confined space entry.

Finally, drones are becoming the primary tool for rapid remote inspection and other activities at heights. These platforms evolve to carry out not just inspection but also maintenance tasks. They represent the objective: transforming a high-risk human activity into a safe, remote, and automated operation.

ONE STEP AT A TIME REDUCING ELEVATED WORK

The path from manual work at heights to automated robotics is not a single jump, but a series of sequential steps. Positioned between manual methods like scaffolds / cranes and robotic systems is a growing category of technologies designed for human augmentation. These solutions don't aim to replace the skilled technician but to enhance their capabilities by automating the most physically demanding and repetitive aspects of their work, directly targeting key sources of risk.

A prime example is the Lifting Bot, a robotic system that automates the vertical transport of materials on industrial sites. The task of manually carrying heavy components up and down a structure is a major source of worker fatigue and a critical human factor in fall-related incidents. By taking over this strenuous activity, the LiftBot allows workers to focus on their value added task.

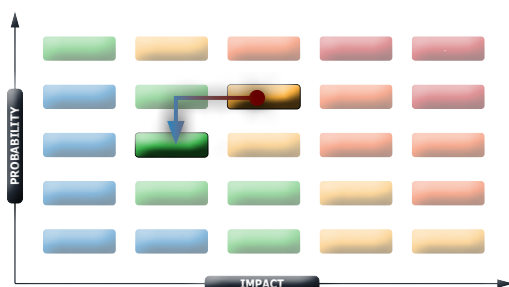
This significantly reducing physical strain and the number of hazardous trips.



a battery powered lifting bot transports equipment to workers at heights

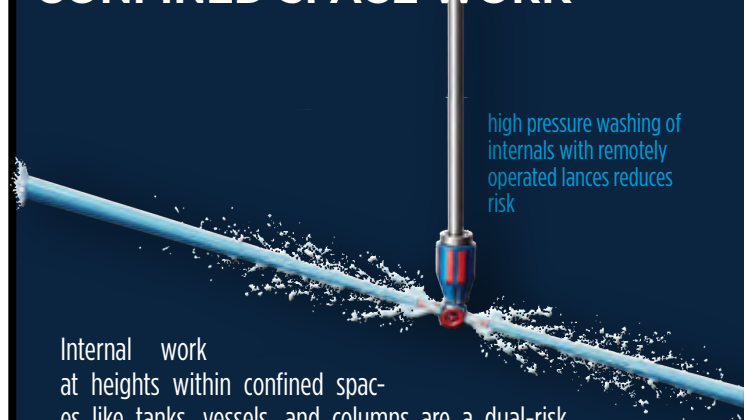
This technology is already being deployed at many Chevron sites, significantly reducing crane usage and man hours at risk.

less walking up and down while carrying heavy equipment reduces probability and impact



MANIPULATORS FOR CONFINED SPACE WORK

high pressure washing of internals with remotely operated lances reduces risk



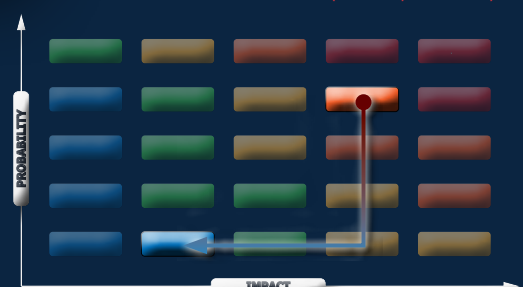
Internal work at heights within confined spaces like tanks, vessels, and columns are a dual-risk environment. The first step to increase safety is in eliminating human entry. This often involves simple, effective remote visual inspection tools. Pan-Tilt-Zoom (PTZ) cameras, mounted on long telescopic poles or lowered on reinforced cables, can be inserted through manways to provide a comprehensive remote view of a tank's interior. These systems allow inspectors to identify corrosion, check weld integrity, and assess the overall condition of internal surfaces from a safe distance, effectively eliminating the need for a person to enter the confined space for initial visual checks.

Leaping beyond passive viewing, more advanced systems are emerging that enable active intervention. Manway-mounted robotic arms represent the next generation of non-entry solutions. These systems feature multi-axis, articulated arms that can be temporarily fixed to a side or roof manway, extending deep into the vessel. Equipped with high-pressure nozzles, cameras, and lights, a remote operator can perform tasks ranging from cleaning to detailed visual inspections, all without requiring risky human entry.

high resolution cameras are used to visually inspect internals remotely



avoiding scaffolding and human entry in confined spaces significantly reduces probability and severity



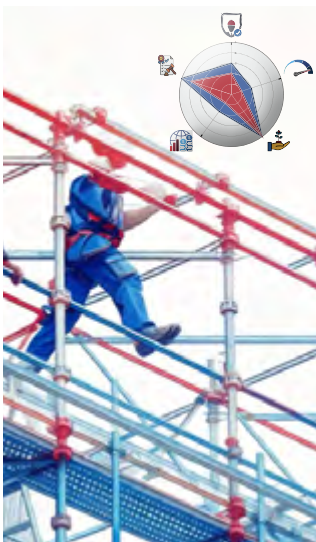
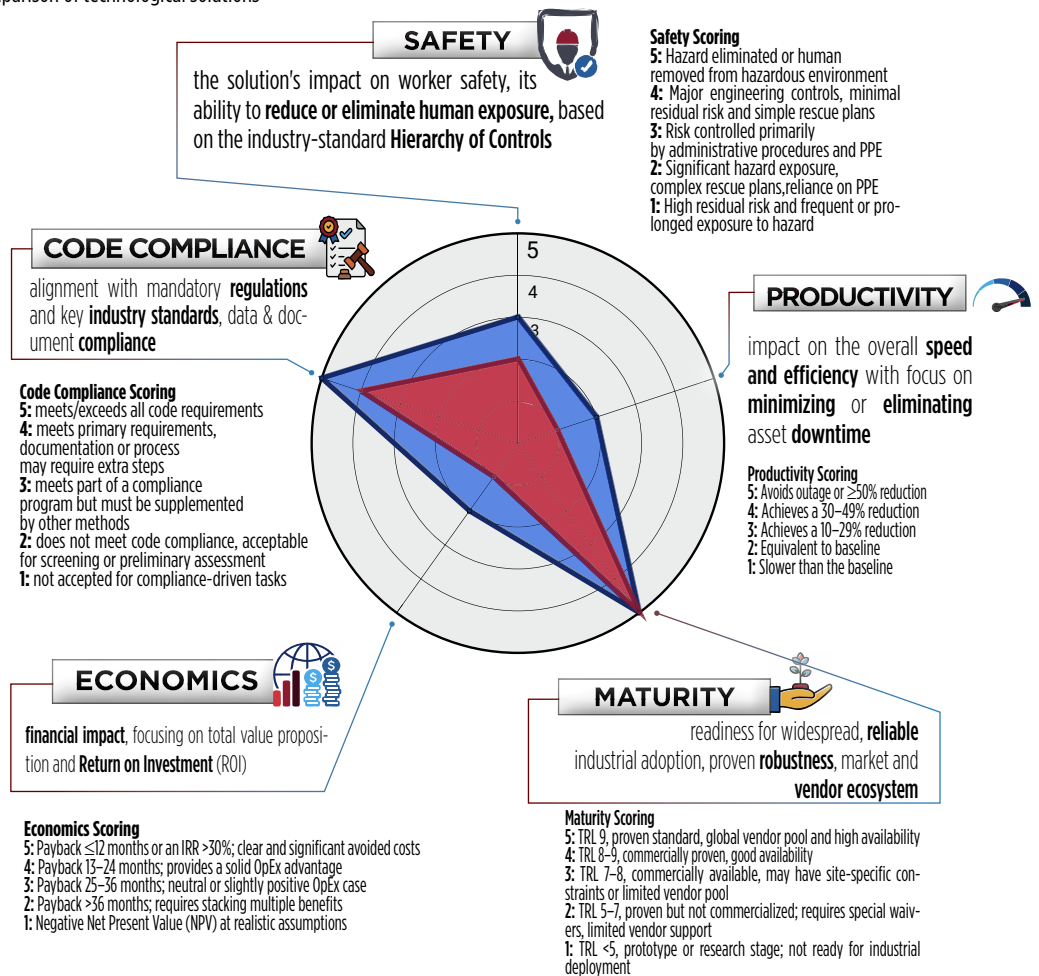
SOLUTION FIT

defining metrics for qualitative comparison of technological solutions

Risk and safety are the most important factors driving the transition to better methods for elevated works. In order to understand the full potential of new technologies we need to assess it from various angles. Therefore we are introducing a five axis evaluation matrix. In addition to **Safety** we rate **Productivity**, **Maturity**, **Economics**, and **Code Compliance**. Depending on asset type, planned/unplanned work, budget restrictions, and data insights this will contribute to understanding the right method to use.

We have defined a clear guideline on how to score each metric from 1 to 5 and for every solution we discuss we provide our own, qualitative and objective rating in a spider graph.

This is a qualitative rating system based on experience and market feedback from asset owners as well as technology providers.



Scaffolding – External



3 major engineering control that provides a stable work platform, but it does not eliminate the fall hazard. Significant residual risk from falls, dropped objects, and collapse persists, requiring reliance on PPE and complex rescue plans.



2 traditional baseline for comparison. The process is notoriously slow, with deployment and dismantling taking days or even weeks, which can cause significant project delays and asset downtime.



5 universal industry standard for access, with a massive and mature global vendor pool for both materials and certified labor.



2 characterized by high direct costs for rental, transport, and labor, and significant indirect costs from downtime. The payback is very long as it is a necessary cost, not an efficiency-improving investment.



5 explicitly and rigorously governed by OSHA standards (e.g., 1926 Subpart L). When erected by certified professionals, it directly meets all code requirements for providing a compliant work platform, and the process is fully auditable.

Scaffolding – Internal/Confined

2 combines all the risks of external scaffolding with the severe, high-consequence hazards of confined space entry (atmospheric, chemical, entrapment). It significantly increases the duration and severity of hazard exposure for workers, and rescue is far more complex.

1 slowest access method by a large margin. It requires extended asset downtime for draining, cleaning, purging, and ventilation before the complex internal build can even begin, making it a major bottleneck in any turnaround schedule.

5 TRL 9. The underlying technology is identical to external scaffolding and is the standard practice for major internal work. The labor pool is more specialized (requiring confined space certification) but is still mature and widely available.

1 most expensive access option. It combines the high direct costs of a complex build with the extreme indirect costs of extended, full asset downtime. The economic value is negative; it is a high cost that must be borne for essential tasks.

4 meets code requirements if all regulations for both scaffolding and confined space entry (OSHA 1910.146) are followed. The score is slightly lower due to the significantly higher complexity and dual regulatory burden, which increases the potential for compliance failures.

VISUAL INSPECTION AT ELEVATION

Visual inspection is the cornerstone of any effective asset integrity program. It is the first line of defense in identifying potential issues such as corrosion, structural damage, coating failures, and leaks before they escalate into costly failures. This fundamental task is performed at varying frequencies across all industrial assets.

For external inspections, Unmanned Aerial Vehicles (UAVs), or drones, have become a transformative

visual and thermal cameras, these drones can be deployed rapidly to capture detailed, geolocated imagery of tall and complex structures like flare stacks, storage tanks, and process columns. The most significant productivity advantage is the ability to conduct these inspections while the asset remains live and in operation, eliminating the need for production shutdowns.



industrial drone with high resolution camera

technology. These range from standard quadcopters for visual/thermal to advanced systems capable of Beyond Visual Line of Sight (BVLOS) operation. Equipped with high-resolution vi-

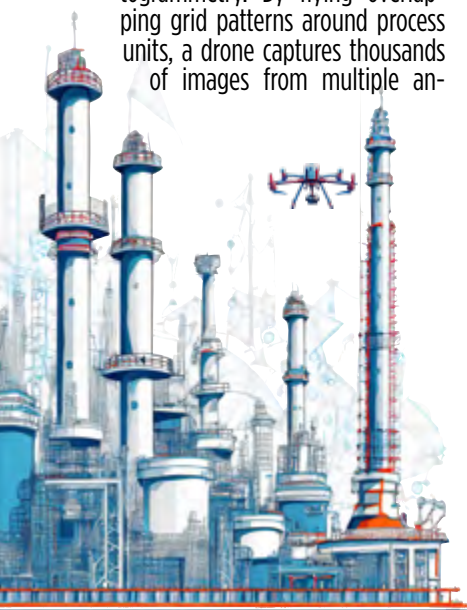
ual inspection that would traditionally take weeks using scaffolding can often be completed in a single day, providing a comprehensive dataset that is safer, faster, and more cost-effective to acquire.

TECH INSIGHT

PHOTOGRAMMETRY

Drones equipped with high-resolution cameras create detailed 3D maps through a process called photogrammetry. By flying overlapping grid patterns around process units, a drone captures thousands of images from multiple an-

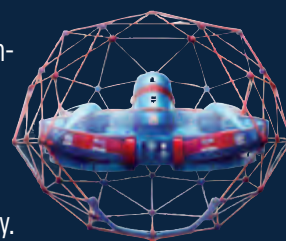
gles. Specialized software stitches these images together to generate a dimensionally accurate, photo-realistic 3D model. This "digital twin" serves as a powerful tool for asset integrity management, allowing to perform remote visual inspections, annotate findings like corrosion or structural defects directly onto the model, and precisely track changes over time by comparing scans from different periods.



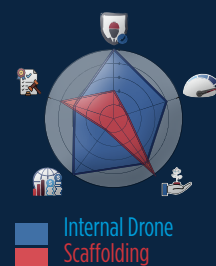
INSIDE CONFINED SPACES

For the high-risk environment of internal, confined space inspections, specialized collision-tolerant or "caged" drones are a proven method for internal visual inspection. These drones are designed to navigate inside assets like tanks, boilers, and pressure vessels without GPS, using onboard lighting to capture clear video of internal surfaces and components.

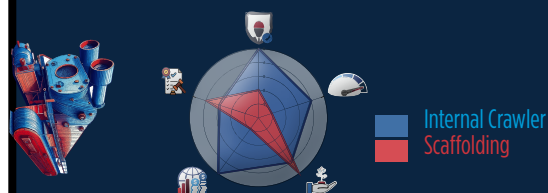
This technology effectively eliminates the need for hazardous human confined space entry for initial visual screening, which is one of the most dangerous activities in the industry. By removing the need to build internal scaffolding, caged drones can reduce inspection-related downtime from over a week to a matter of hours.



collision tolerant cage drone for confined space inspection



CLOSEUP INSPECTION



Visual inspection crawlers (magnetic or suction based) are robust, remotely operated robots. Compared to drones, they perform more detailed assessments inside confined spaces. Flight time or visibility caused by dust are not an issue. Typically, equipped with high-definition Pan-Tilt-Zoom (PTZ) cameras and powerful lighting, an operator can safely navigate the crawler through an emptied and prepared asset, such as a storage tank, pressure vessel, or large-diameter pipeline. This allows for close-up examination of welds, coatings, and internal surfaces, identifying defects like corrosion, pitting or cracking. Both, drones and crawler systems provide a direct, recordable, repeatable and safer alternative to sending a person inside for visual assessments.

ULTRASONIC THICKNESS MEASUREMENT

high value use case for structural integrity assessment at heights

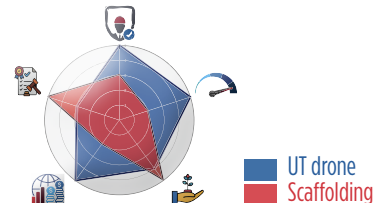
Ultrasonic Thickness (UT) measurement is a critical non-destructive evaluation (NDE) method for assessing the integrity of steel assets by spot measuring wall thickness to detect corrosion and erosion.

The highest return on investment (ROI) for drone-based UT is found in applications where inspections can be performed while the asset remains in service, completely avoiding costly production shutdowns. The prime example is the inspection of live flare stacks in refineries and offshore platforms. Traditionally, this requires a multi-day shutdown for cooling and access, but a UT drone can take measurements on the hot, operational stack, with very high savings in lost production. When the drone is available on site, setup time is

less than 30 minutes, compared to hours for climbers or days for scaffolding. Other high-ROI use cases include inspecting the upper shell courses and roofs of large above-ground storage tanks and the hulls of Floating Production, Storage, and Offloading (FPSO) vessels. In these scenarios, the drone's ability to access elevated or hard-to-reach areas eliminates the need for massive, expensive scaffolding builds, rope access or taking a vessel out of service. This translates into enormous cost and time savings, and reduces risk.

drone with UT payload performs wall thickness checks at heights.

Setup time : 30 minutes
Flight time: up to 15 minutes
Max. Temperature: 260°C (500°F)



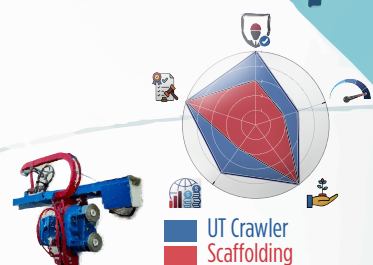
TANK AND PRESSURE VESSEL INTEGRITY INSPECTION

using UT crawlers for full coverage of walls at heights

UT crawlers provide new insights in asset integrity management by generating a C-scan, a detailed, color-coded "heat map" of an asset's remaining wall thickness. This high-density data is invaluable for inspecting large steel assets like storage tanks and pressure vessels. While industry standards like API 653 and API 510 mandate periodic thickness measurements, they do not specify the deployment method.

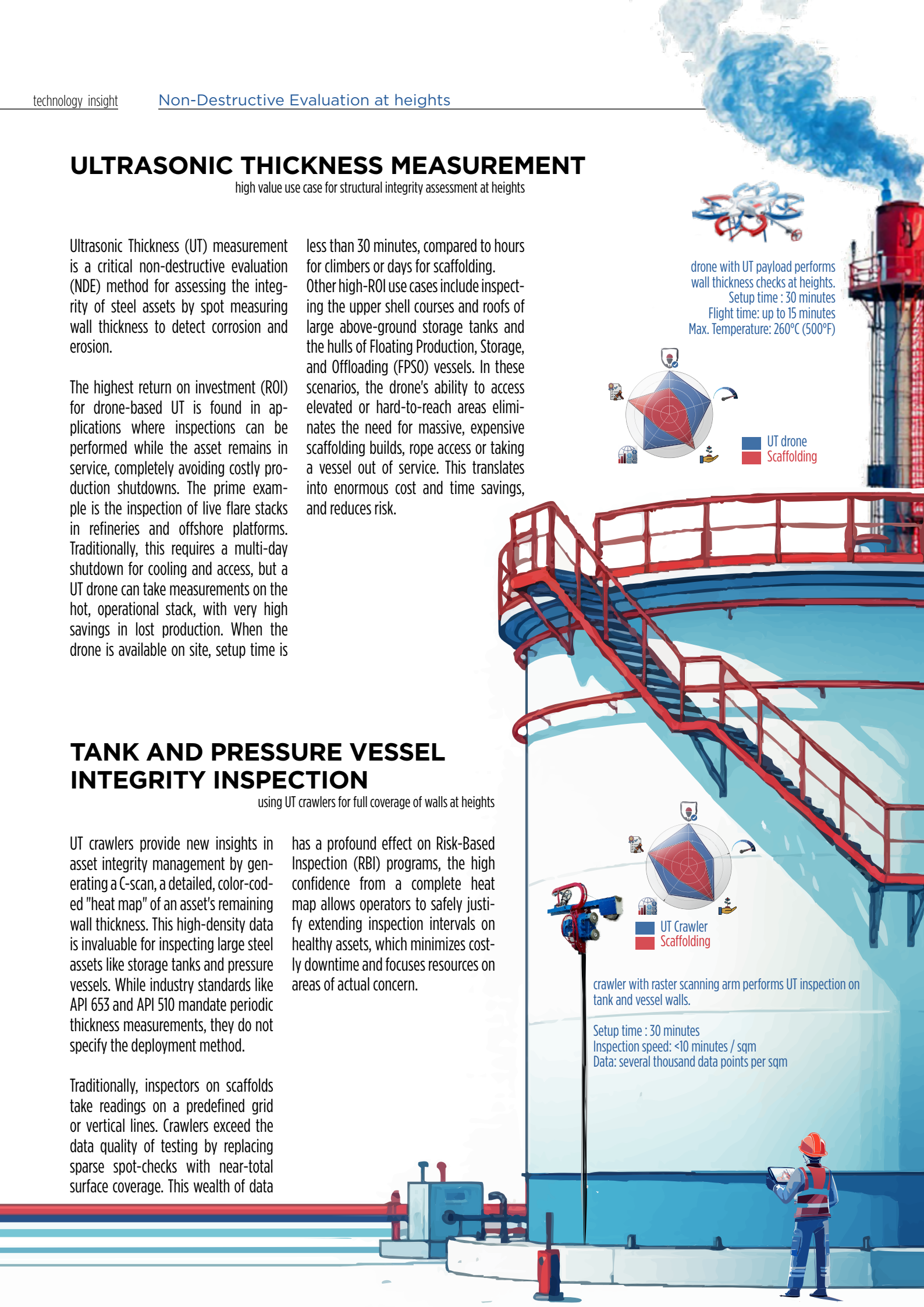
Traditionally, inspectors on scaffolds take readings on a predefined grid or vertical lines. Crawlers exceed the data quality of testing by replacing sparse spot-checks with near-total surface coverage. This wealth of data

has a profound effect on Risk-Based Inspection (RBI) programs, the high confidence from a complete heat map allows operators to safely justify extending inspection intervals on healthy assets, which minimizes costly downtime and focuses resources on areas of actual concern.



crawler with raster scanning arm performs UT inspection on tank and vessel walls.

Setup time : 30 minutes
Inspection speed: <10 minutes / sqm
Data: several thousand data points per sqm



INTERNAL NDE

Human entry into confined spaces is a complex, high-risk, and time-consuming operation. The process requires the asset to be taken offline, drained, cleaned, and thoroughly purged to ensure a safe atmosphere. A multi-person

team is mandatory, including not only the inspector entering the space but also a dedicated attendant (or "watchman") stationed at the manway to monitor the entrant, and a fully-equipped, trained rescue crew on

standby for immediate response in case of an emergency. Continuous gas monitoring and strict permitting processes add significant administrative overhead.

MAGNETIC & SUCTION CRAWLERS CAGED DRONES

■ UT crawler
■ Internal Scaffolding

Robotic confined space crawlers are becoming a robust solution for performing NDE inside confined spaces like storage tanks, pressure vessels or boilers. These semi-autonomous robots are deployed through a manway, adhering to the walls or roof with powerful magnets or suction technology. They can navigate complex internal geometries, even around obstacles like baffles and agitators, while carrying NDT payloads.

UT drones represent a highly agile technology for performing NDE at elevation in confined spaces. With collision tolerant cages, they are capable of flying in dark,

GPS-denied environments to perform spot thickness measurements. The drone flies to a specific location, presses its UT probe against the surface (dispensing a couplant gel), and records a precise thickness reading. New advanced systems can even **clean the measurement spot** with a wire brush

before testing. While they typically provide spot readings rather than full C-scans, their speed and ability to reach virtually any point within a large tank make them an invaluable tool for **rapid assessment and targeted data collection** without human entry.

confined space drone
for spot cleaning and
UT inspection

■ Internal drone
■ Internal Scaffolding

TECH INSIGHT LIDAR

To map the interior of confined spaces, LiDAR (Light Detection and Ranging) sensors are used. As the device navigates through a dark, GPS-denied environment the LiDAR sensor creates a 3D point cloud of the internal structure. It works by emitting laser pulses and measuring

the time it takes for the light to reflect off surfaces and calculates the distance. The technology not only enables safe navigation but also produces a 3D map of the inside. It allows for internal measurements crack dimensions, and deformations, providing quantitative data.

PIPE INSPECTION AND MAINTENANCE

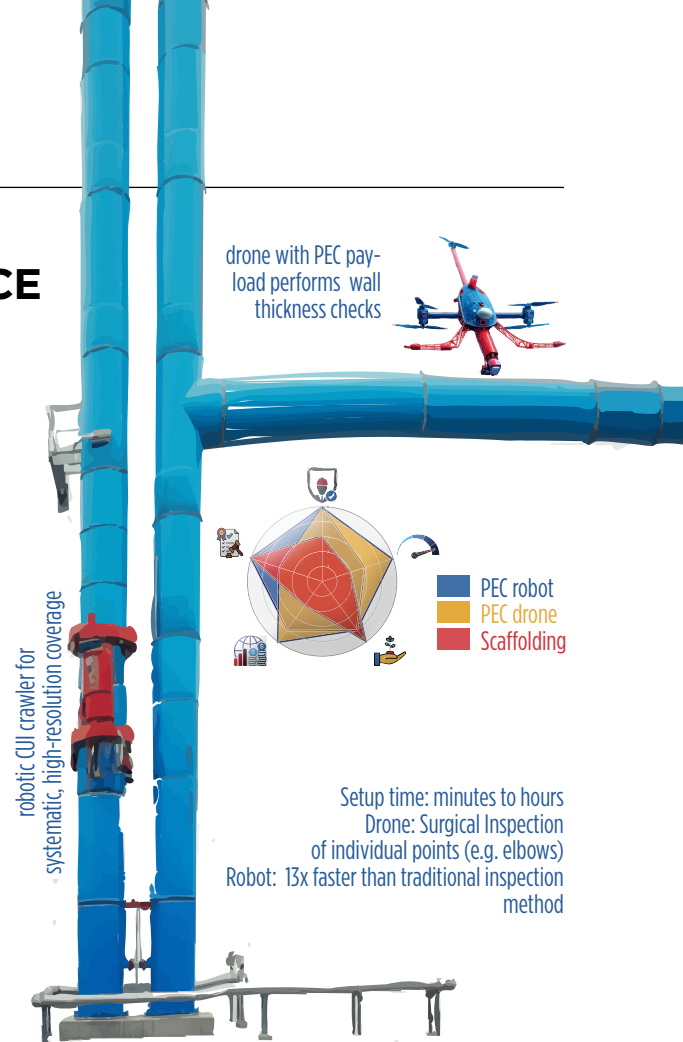
emerging use cases for elevated pipe assessment

The operational integrity of in-service process piping in oil and gas is governed by API 570. The code references complementary practices, risk-based inspection (RBI) and fitness-for-service (FFS), to help prioritize work and make sound engineering decisions. RBI focuses inspection resources, time, and budget on the assets that pose the greatest risk so teams can confidently set inspection intervals. FFS (per API 579) evaluates corrosion rates, calculates remaining life, and supports decisions on repair, replacement, or rerating. Both methods depend on high-quality inspection data.

For elevated piping, corrosion under insulation (CUI) is a significant safety and cost driver, often representing

a large share of piping maintenance spend. During planned turnarounds, API 570 programs typically call for inspection of high-risk CUI locations. Conventional methods involve scaffolding or rope access, removing insulation, visual examination and ultrasonic testing, and then re-insulation.

A newer non-intrusive screening method, pulsed eddy current (PEC) can detect wall-loss trends through insulation and weather jackets. Handheld PEC probes are now being integrated on robotic crawlers and drones, reducing scaffolding hours, improving safety for personnel working at heights, and helping optimize turnaround schedules.



PHYSICAL WORK & CLEANING

beyond inspection



A common concern with robotic and drone inspection is what happens after a defect is found. If corrective work requires scaffolding or rope-access teams, the added mobilization can erode the value case. To address this inspection-to-action gap, more platforms now integrate tools that perform defined maintenance tasks, reducing follow-on work and exposure at height.

Foreign object search and retrieval (FOSAR) is one example. In confined spaces, robots equipped with manipulators can locate, grasp, and remove loose debris, fasteners, or tools, this is helping prevent equipment damage and unplanned downtime while limiting human entry and work at heights.

Beyond detection, newer developments support remote asset maintenance.

These platforms can execute targeted spot repairs, such as surface preparation, grinding, and application of paints or protective coatings, at height. The result is fewer hours of working at heights and a more streamlined path from inspection finding to documented repair.

Robotic cleaning solutions extend this capability on hard-to-reach structures. Purpose-built units deliver high-pressure washing and surface prep on tanks, offshore production and drilling rigs, and floating production storage and offloading (FPSO) units.

Applied correctly, these tools enhance safety and reliability by minimizing exposure at heights and keeping critical assets in service.

FROM ASPIRATION TO ADOPTION

The evidence supporting robotic solutions for working at heights is compelling. Documented case studies report up to 98% reductions in inspection time, single-event savings on the order of €450,000 for a boiler inspection, and the avoidance of costly downtime of facilities. Most importantly, these platforms remove human exposure during the task to fall hazards and confined-space entry. However, widespread adoption is not a simple “plug-and-play” exercise. Production sites rightly apply rigorous barriers to implementation that must be addressed with disciplined change management as well as operational realism.

The most common **pushbacks are not technical, but human**. Concerns like “robots will eliminate our jobs” or phrases like “we have always done it that way” are the most obvious. This deserves proactive management. Data from deployments shows the inspector’s primary responsibility, judging asset integrity, remains, while the high-risk routine of climbing or crawling is reduced or eliminated. The role is upskilled to robot operator and data analyst, supported by training, competency frameworks, and clear career pathways. This shift improves safety outcomes while increasing the value of human expertise in planning, diagnosis, and risk assessment.

A second hurdle is the **perception of technological immaturity** and risk. Site managers are right to ask whether a new device could fail, and to consider new risk vectors, such as explosion-proof rating, a drone’s wind envelope, radio-link loss, electromagnetic interference, or the cybersecurity posture of a networked crawler. These are not showstoppers; they are inputs to a formal Management of Change (MOC) process. Risks should be engineered out where feasible and verified through pre-deployment trials and acceptance criteria.

Compliance is the next question: “Will API or ASME accept this data?” This barrier is being reduced. API standards now include

provisions that recognize in-service robotic inspection under defined conditions, and leading vendors are building platforms and workflows to align with standards. The direction is clear: robotic methods must meet procedure, calibration, and competency requirements, the resulting data must support compliant decisions.

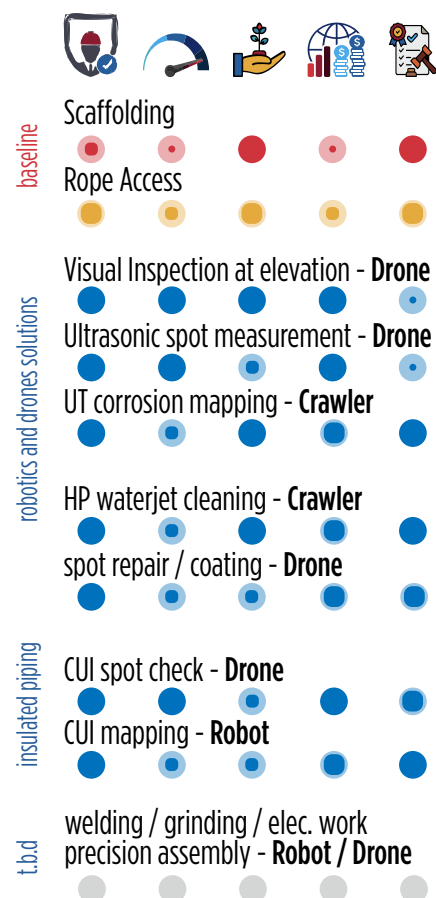
Asset Owners and Industrial Service Providers should move from isolated pilots to standardized deployment. That means formalizing the MOC process for robotics, integrating robotic data with risk-based inspection (RBI) and fitness-for-service (FFS) decision workflows, and investing in the “human MOC”, meaning training, certifications, and upskilling for the existing workforce. Establish clear KPIs (e.g., personnel hours at elevation eliminated, coverage achieved, data quality indices, turnaround critical-path reductions) and govern with lessons-learned loops.

Robotics Developers and Academia should target the next set of constraints: higher degrees of autonomy, sensor and actuator hardening for temperature, moisture, and EMI; improved localization and mapping in repetitive geometries; and secure-by-design architectures that align with industrial best practices.

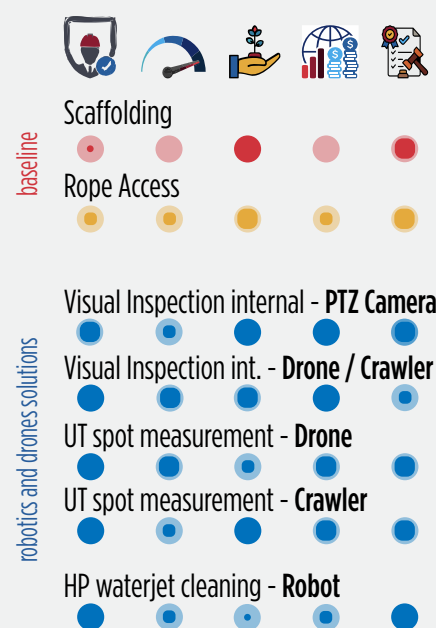
Policymakers and Standards Bodies hold an important lever. Accelerating acceptance of robotic inspection, moving from a novel “alternative” to an accepted baseline for compliance, will provide clarity and unlock needed investment. When regulators and standards bodies codify robotic inspection methods as a baseline option for compliance, the market will respond at scale and adoption will move toward widespread, near-universal practice where appropriate.

This joint effort is a practical path to reduce persistent risks, improve reliability, and transition asset management from a reactive, manual-first model to a safer, predictive, robotics-enabled standard.

working at heights EXTERNAL SOLUTIONS



working at heights CONFINED SPACES



CALL TO ACTION

collaboration is the key

Join the robotics journey where innovation meets purpose. The case for action is clear. Proven robotic tools remove exposure at height, deliver higher data quality, and keep critical assets online. The next step is disciplined deployment. Start with the tasks that carries the greatest risk and the strongest return. Integrate robotic data into risk based inspection and fitness for service workflows so findings translate into better decisions faster. Set clear measures of success such as hours at height avoided, coverage achieved, defect detection rates, turnaround days saved, and cost reduced. Share results and lessons learned so each job is safer and more efficient than the last.

Chevron's Robotics program is advancing this shift through practical demonstrations, structured learning, and open collaboration with asset owners, service providers, technology

developers, and standards organizations. We share what works, what needs refinement, and how to scale safely across complex operations. We convene partners, contribute insight to industry forums, and support the development of procedures that help robotic data meet code expectations. This is how thought leadership creates momentum for the entire sector.

Your participation is essential. Field teams know the tasks that drive risk and delay. Engineers translate those needs into requirements that robots can meet. Service providers bring specialized skills and disciplined execution. Developers harden platforms for real sites and real conditions. Regulators and standards bodies clarify acceptance and build confidence. When each group leans in, barriers fall and adoption accelerates.

Make a clear commitment to pilot with purpose, document outcomes, and scale what meets safety, reliability, and cost objectives. Upskill inspectors and technicians so they become robot operators and data analysts with defined competencies and career paths. Align procurement, maintenance, and integrity teams so the right platform shows up with the right payload, procedure, and quality control. Capture data with traceability and metadata so you can trend condition over time and target the next intervention precisely.

This is our invitation and our promise. Together we can protect people, push boundaries, and keep the world moving safely. Collaboration turns technology into results. Join us.

ABOUT THE AUTHORS

The authors are a joint team from Chevron's Technology, Projects, and Execution team and industry experts. We welcome collaboration, reach out to compare lessons learned, explore pilot opportunities, and accelerate safe, reliable adoption together.



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ABBREVIATIONS AND ACRONYMS

AST / AGT	Aboveground Storage Tank; common industry acronym used in API/ASME contexts
API	American Petroleum Institute.
API 570	Piping Inspection Code: In-Service Inspection, Rating, Repair, and Alteration of Piping Systems.
API 579	Fitness-for-Service (FFS) standard and assessment methodology.
API 653	Tank Inspection, Repair, Alteration, and Reconstruction standard.
ASME	American Society of Mechanical Engineers.
CUI	Corrosion Under Insulation.
EEMUA	Engineering Equipment and Materials Users' Association.
EMI	Electromagnetic interference.
FFS	Fitness-for-Service; engineering evaluation supporting repair, replacement, or rerating decisions.
FOSAR	Foreign Object Search and Retrieval.
FPSO	Floating Production, Storage and Offloading unit.
KPI	Key Performance Indicator.
LiDAR	Light Detection and Ranging; optical remote-sensing for 3D mapping.
LOTO	Lockout/Tagout; energy-isolation safety procedure.
MOC	Management of Change; formal process to assess and control risk when introducing changes.
NDT	Nondestructive Testing.
PAUT	Phased Array Ultrasonic Testing.
OSHA	Occupational Safety and Health Administration.
PEC	Pulsed Eddy Current; through-insulation screening for wall-loss trends.
RBI	Risk-Based Inspection; methodology that prioritizes inspection based on risk.
RVI	Remote Visual Inspection.
SOP	Standard Operating Procedure.
TAR	Turnaround; planned outage for inspection and maintenance.
TRL	Technology Readiness Level; scale for technology maturity.
UT	Ultrasonic Testing.

SOURCES AND REFERENCES

1	OSHA 1926.452 - Additional requirements applicable to specific types of scaffolds.
2	https://www.acuren.com/blog/rope-access-vs-scaffolding-comparison-guide/
3	Global installed fleet: 350,000: This is not a total count of all tanks (which is in the millions) but a specific, focused estimate of the large-scale industrial tanks relevant to this report (e.g., in Oil & Gas, Chemicals). This figure was established from market data and validated against a database of bulk liquid storage terminals, which alone contain nearly 100,000 tanks. Estimated Annual Spend: \$4.2B: This is a modeled result. It was calculated using the formula: (350,000 fleet) x (Annual Event Frequency) x (Blended Cost Per Event). Frequency is based on API 653 5-year external and 10-20 year internal cycles, the blended cost was calculated at \$45,000 per event.
4	Global installed fleet: 22,000,000: This is a modeled number, as no direct census exists. It was derived by taking the annual market for new vessels (approx. \$55B), dividing by an assumed average unit cost (\$75,000) to find new units per year (733,000), and multiplying by an assumed 30-year asset lifespan. Estimated Annual Spend: \$23.1B: This is a modeled result. It uses the same formula: (22,000,000 fleet) x (Annual Event Frequency) x (Blended Cost Per Event). The frequency is based on API 510 5-year and 10-year cycles, and the blended cost was calculated at \$3,500 per event.
5	Global installed fleet: 400,000: This is a modeled number. It was derived by taking the annual market for new columns (approx. \$2.0B), dividing by an assumed average unit cost (\$200,000) to find new units per year (10,000), and multiplying by an assumed 40-year asset lifespan. Estimated Annual Spend: \$7B: This is a modeled result. It was calculated as: (400,000 fleet) x (Annual Event Frequency) x (Blended Cost Per Event). The frequency is based on a typical 3-5 year TAR (Turnaround) cycle, and the blended cost was calculated at \$70,000 per event.
6	This is the final modeled estimate from the analysis. Because piping is measured in "millions of miles" rather than units, this figure was derived by analyzing the work required during 3-5 year TAR cycles and is presented as the total annual market value for this asset category.
7	https://oshwiki.osha.europa.eu/en/themes/human-error
8	https://www.health.ny.gov/environmental/investigations/face/training/docs/confined_space_awareness_training.pdf

