TCR ADVANCED ENGINEERING

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AiOM®

Asset Integrity Optimization & Management

for Process Industries

Delivering operational excellence through integrated risk, reliability, and digital intelligence.

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A WORD FROM THE MANAGING DIRECTOR

Foreword

Why we wrote this paper

In 1999, when we founded TCR Advanced Engineering, the term “asset integrity” barely existed in Indian process industry vocabulary. Inspection was something you scheduled. Failure was something you fixed. Reliability was something you hoped for. The instruments were simpler, the budgets tighter, and the science less generous than it is today. Twenty-five years and more than nine thousand investigations later, I can say with some confidence that we have learned three things.

The first is that every failure tells a story, and a well-investigated failure is the most powerful teacher in our industry. We did not build TCR Advanced by chasing every client. We built it by listening to what assets were telling us, often in microstructures that only a metallurgist could read. The discipline of going beyond the broken part to the mechanism that broke it, to the operating decision that fed the mechanism, to the design choice that left the door open in the first place, is what makes failure investigation an engineering craft rather than a clerical one.

The second is that the gap between data and decision is where most integrity programmes fail. The Indian process industry today is not short of inspection data. It is short of engineering interpretation. The most sophisticated ultrasonic scan in the world is worthless if no one in the room understands the damage mechanism that produced the indication, and a perfectly executed RBI study is dangerous if the damage mechanism on which it rests is the wrong one.

The third is that the next decade will belong to operators who combine metallurgical depth with digital intelligence, and have the patience to do both properly. I have spent the past several years building this conviction into a framework we call AiOM®—Asset Integrity Optimization & Management. It is not a product. It is the way we think. It is what happens when a fifty-year engineering tradition meets a five-year digital toolkit, and neither one apologises for the other. It is the framework we use ourselves, in our own laboratories at Makarpura and on plants from Vadodara to Vizag to Jubail, and it is the framework we now offer to any operator who is tired of fighting fires their inspection programme should have caught.

This paper is written for plant managers, integrity engineers, and operations leaders who carry the daily weight of keeping aging assets running safely. It is also written for the next generation of engineers entering this field, the ones who will need to be fluent in both microstructures and machine learning, and who will inherit the assets we are running today. I hope you find it useful. If you do, write to me. The best conversations in our industry happen one engineer to another.

Paresh Haribhakti
Managing Director, TCR Advanced Engineering
Vadodara, 2025

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Executive Summary

The global process industry stands at a pivotal moment. More than eight hundred billion dollars are lost every year to equipment failures and unplanned shutdowns. Sixty per cent of refinery and petrochemical assets are operating beyond their original design life. The traditional approach to inspection and maintenance, organised around fixed intervals and compliance checklists, can no longer deliver the reliability, safety, and profitability that the industry demands of itself.

AiOM®—Asset Integrity Optimization & Management—is TCR Advanced Engineering's integrated framework for transforming asset integrity from a compliance function into a strategic value driver. By systematically combining Risk-Based Inspection (RBI), Fitness-for-Service (FFS), Reliability-Centred Maintenance (RCM), and advanced digital technologies, AiOM® enables process plant operators to prioritise inspection resources where they matter, prevent catastrophic failures before they happen, and extend asset life with confidence and defensibility.

Five insights that define the AiOM® opportunity

$800B+	**Annual cost of equipment failures in global process industries** Unplanned downtime, reactive maintenance, regulatory fines, environmental penalties—the bulk of it preventable with a disciplined AiOM® programme.
60%	**Of global refinery and petrochemical assets are operating beyond original design life** Life extension is now the dominant capital strategy. It demands integrity management that is rigorous, integrated, and metallurgically literate, or it becomes a quiet liability.
40–60%	**Of all process plant piping failures are attributable to Corrosion Under Insulation** The most prevalent—and most systematically neglected—damage mechanism in our industry. AiOM® addresses it at its root.

30–50%	**Reduction in unplanned shutdowns achievable with mature AiOM® implementation** Operators with integrated RBI and predictive maintenance programmes consistently outperform their peers on equipment availability, safety, and turnaround discipline.

Gen. 5	**The AI-augmented era of asset integrity is here** Digital twins, machine-learning damage models, and IoT-enabled Integrity Operating Windows are redefining what predictive maintenance means for the 2020s and beyond.

THE BOTTOM LINE

AiOM® is not a tool. It is a management philosophy. When it is implemented with the rigour and engineering depth that TCR Advanced Engineering brings to the work, it converts asset integrity from a cost centre into a competitive advantage—improving safety, extending asset life, and delivering measurable returns from the first year onward.

SECTION 01

The Asset Integrity Imperative

Why the status quo is no longer sustainable

A few years ago, the operations manager of a mid-sized refinery in western India called us late on a Saturday evening. A pressure relief valve on a sour-service line had lifted unexpectedly. Inspection records were clean. The corrosion monitoring programme was current. By every metric the plant tracked, the system was healthy. We were on site by Monday morning. By Wednesday we had identified an aggressive under-deposit corrosion mechanism that the inspection programme had been pointed in entirely the wrong direction to catch. The data had been collected diligently. The wrong question had been asked of it.

Stories like this one are the everyday reality of the process industry. Refining, petrochemicals, power generation, oil and gas, fertilisers, and specialty chemicals operate some of the world's most complex, hazardous, and capital-intensive infrastructure. The reliability of this infrastructure directly determines safety outcomes, environmental performance, regulatory standing, and ultimately, profitability.

Yet despite enormous investment in inspection and maintenance, the industry continues to suffer a fundamental paradox. Extensive activity all too often fails to prevent the failures it was designed to catch. The root cause is a fragmented, compliance-driven approach—one that generates vast quantities of inspection data without the analytical framework to extract decisions from it.

The high cost of reactive maintenance

The economics of reactive maintenance are unforgiving. A single unplanned shutdown at a medium-sized refinery can cost USD 150,000 to USD 250,000 per day in lost production alone, before accounting for emergency repair costs, regulatory investigations, insurance loss-of-profit deductibles, and the long shadow of reputational damage. At the macro level, reactive and ineffective maintenance approaches cost the global process industry an estimated USD 800 billion every year.

> **KEY FINDING**
>
> Industry studies consistently show that eighty per cent of equipment failures are age-independent, which means time-based maintenance schedules—still the dominant approach in most plants—are fundamentally mismatched to actual failure patterns. Only risk-based, condition-driven inspection delivers the kind of reliability improvement modern operations require.

The aging assets crisis

The demographic reality of global process infrastructure is stark. The majority of refinery and petrochemical capacity in the Americas, Europe, and much of Asia was built between the 1950s and the 1980s, making it forty to seventy years old today. These assets were designed for twenty-five to thirty year operational lives. Life extension is not inherently problematic, but it requires a fundamentally different approach to integrity management than the original design ever contemplated.

As equipment ages, corrosion rates accelerate, damage mechanisms evolve, and the consequences of failure grow. Inspection intervals that were appropriate in a plant's first decade become inadequate, and potentially dangerous, in its fourth or fifth. Without a systematic framework for understanding and managing these changes, life extension programmes carry unacceptable risk—and the engineers running them know it.

The ESG and Net Zero imperative

Increasingly, asset integrity is not just an operational issue. It is an ESG issue. Unplanned releases, flaring events, and equipment failures directly affect a company's carbon footprint, its regulatory standing, and its social licence to operate. As net zero commitments proliferate and mandatory emissions reporting expands, the integrity of process equipment is being tied, sometimes explicitly, to the company's sustainability performance.

EMERGING TREND: ESG-LINKED INTEGRITY KPIs

Leading operators are now integrating asset integrity KPIs directly into ESG reporting frameworks. Unplanned flaring rates, process safety events, and hydrocarbon release incidents are becoming headline sustainability metrics, creating a direct financial link between AiOM® programme maturity and corporate ESG ratings.

The digital transformation opportunity

Industrial IoT, digital twins, machine learning, and cloud-based asset management platforms present the industry with an unprecedented opportunity. Real-time sensor data, AI-powered damage prediction models, and drone-assisted inspection are being deployed at leading operators today. But their value is realised only when they are built on a rigorous integrity framework. Technology without methodology is data proliferation, not risk reduction. AiOM® provides the engineering foundation that makes digital transformation genuinely meaningful.

SECTION 02

The Evolution of Asset Integrity Management

From reactive firefighting to AI-augmented precision

The history of asset integrity management is a story of hard-learned lessons—industrial accidents that drove regulatory change, technological advances that opened new possibilities, and evolving best practices that gradually shifted the paradigm from reactive to predictive. Understanding this evolution is essential context for recognising why AiOM® represents a generational step, not merely an incremental improvement.

Generation	Era	Core Philosophy	Primary Limitation
1st Gen Reactive	Pre-1960s	Run-to-failure. Repair equipment when it breaks. Maintenance treated as a necessary cost.	Unpredictable failures, high safety risk, no systematic cost optimisation.
2nd Gen Preventive	1960s–1980s	Time-based maintenance at fixed intervals regardless of actual equipment condition.	Wastes resources on healthy equipment; fails to prevent condition-dependent failures.
3rd Gen Risk-Based	1990s–2000s	API 580/581 RBI evaluates probability and consequence of	Siloed tool, not integrated with reliability, corrosion control, or

Generation	Era	Core Philosophy	Primary Limitation
		failure to prioritise inspection.	real-time operations.
4th Gen Integrated AIM	2010s	RBI, FFS, RCM, IOWs, and CCDs integrated into a unified management system.	Data-heavy but often lacking real-time inputs and predictive analytics capability.
5th Gen AI-Augmented AiOM®	2020s–Present	Digital twins, ML-predicted damage rates, IoT IOW monitoring, drone inspection—built on a rigorous engineering foundation.	Requires both digital maturity and deep integrity expertise to execute well.

Figure 1: Five generations of asset integrity management—from reactive run-to-failure to AI-augmented AiOM®.

The leap to the fifth generation

The transition from fourth to fifth generation AiOM® is not simply about adding technology. It is about fundamentally reimagining what asset integrity management can deliver. In the fourth generation, programmes generated vast quantities of data: inspection records, corrosion monitoring readings, process safety reports. In the fifth generation, that data becomes intelligence—feeding machine-learning models that predict damage, digital twins that simulate failure scenarios, and automated alerts that trigger engineering action well before failures occur.

TCR Advanced Engineering operates at this frontier. We bring two things to it that we believe most of our peers cannot: a metallurgical tradition that runs from the parent TCR Engineering's founding in 1973 to the laboratories we operate today, and an engineering discipline that refuses to treat digital tools as a substitute for understanding. Our AiOM® framework provides the rigorous engineering foundation without which digital instruments produce false confidence rather than genuine risk reduction.

SECTION 03

The AiOM® Framework

Eight integrated disciplines, one unified system

AiOM® is not a single tool or a checklist. It is an integrated management framework comprising eight complementary disciplines. Each one addresses a specific aspect of asset integrity; together they create a system whose value is considerably greater than the sum of its parts. The power of AiOM® lies in the integration. Insights from one discipline continuously inform and improve all the others.

Tool 01 · Risk-Based Inspection (RBI)

RBI is the cornerstone of the AiOM® framework. Based on API 580/581 and supported by API 584, it evaluates both the probability of failure—driven by active damage mechanisms and current condition—and the consequence of failure—driven by process fluid inventory, toxicity, flammability, and business impact—for every item of pressure-containing equipment in the plant.

- Prioritises inspection resources on the highest-risk equipment, where inspection matters most.
- Enables risk-informed interval optimisation, extending intervals on low-risk items to free resources for genuine threats.
- **2025 enhancement:** integration with ML-predicted corrosion rate models enables dynamic, real-time risk score updates based on actual operating conditions, not static historical averages.

Tool 02 · Fitness-for-Service (FFS)

When equipment contains flaws—corrosion, cracks, dents, or other damage—FFS assessment per API 579-1/ASME FFS-1 and BS 7910 provides the rigorous analytical basis for determining whether the equipment can continue safely in service, under what conditions, and for how long.

- Prevents unnecessary replacements by quantifying remaining life so that informed run, repair, or replace decisions can be made.
- Enables risk-managed run-to-next-turnaround decisions, avoiding the cost and risk of unplanned emergency shutdowns.
- **2025 enhancement:** FFS assessments increasingly use digital twin data, comparing actual measured profiles to ML-predicted corrosion for conservative-yet-optimised remaining life estimates.

Tool 03 · Reliability-Centred Maintenance (RCM) and FMEA

RCM (SAE JA-1011, JA-1012) and Failure Mode and Effects Analysis ensure that maintenance activities are designed around the actual failure modes of equipment and their consequences, not arbitrary time-based schedules. The result is a maintenance programme that is simultaneously more effective and more efficient.

- Identifies dominant failure modes for each equipment category, enabling targeted consequence-driven maintenance.
- Eliminates tasks that provide no reliability benefit, reducing cost without increasing risk.

Tool 04 · Integrity Operating Windows (IOWs)

IOWs as defined in API 584 establish the safe operating envelope for process variables—temperature, pressure, flow rate, corrodent concentration, pH—within which equipment integrity is maintained. Exceedances trigger inspection or maintenance responses before damage accumulates to the point of consequence.

- Closes the operational loop between process engineers and integrity engineers, ensuring that exceedances are recognised as integrity events rather than mere process deviations.
- **2025 enhancement:** IoT-enabled real-time IOW monitoring transforms these from static documents into live integrity management tools, with automated alerts when variables approach critical limits.

Tool 05 · Corrosion Control Documents (CCDs)

CCDs per API 970 systematically capture the corrosion and damage mechanisms active in each process unit, documenting damage cause, affected materials and components, likely damage location and morphology, severity and rate, and recommended inspection methods and frequencies. The CCD is the single source of truth for corrosion engineering knowledge in each unit, and a well-maintained set of CCDs is, in our experience, one of the most reliable predictors of integrity programme maturity.

Tool 06 · Management of Change (MOC)

A disciplined MOC process ensures that changes to process chemistry, operating conditions, materials of construction, or equipment configuration are evaluated for their integrity impact before implementation. Many major failures in this industry have been precipitated by process changes that looked minor on the day they were approved, but that inadvertently introduced new damage mechanisms or accelerated existing ones.

Tool 07 · Quality Assurance Programme (QAP)

QAP ensures that inspection activities generate reliable, reproducible, and properly documented data—the foundation upon which all integrity decisions rest. It encompasses inspector qualification, NDE technique validation, data management protocols, and routine auditing. At TCR Advanced, this is non-negotiable: it is the reason our laboratories carry NABL/ISO 17025 accreditation across chemical, mechanical, metallographic, and NDT disciplines, and why our reports stand up in regulatory review.

- **2025 enhancement:** AI-assisted NDE interpretation, including machine-learning models trained on PAUT and TOFD datasets, is improving detection sensitivity and reducing operator-dependent variability across inspection campaigns.

Tool 08 · Root Cause Analysis (RCA)

When failures occur, rigorous RCA—going beyond the immediate cause to identify contributing factors and systemic weaknesses—is how an AiOM® programme learns and continuously improves. RCA findings feed back into the RBI database, the CCDs, and the IOW limits, strengthening the entire framework over time. Without this loop, an AiOM® programme stops being a learning system and becomes simply another archive.

> **FRAMEWORK INTEGRATION**
>
> The true power of AiOM® lies in cross-tool integration. An IOW exceedance triggers an RBI risk profile update and may initiate an FFS assessment. An RCA finding updates the CCD and may revise IOW limits. A process MOC triggers RBI re-evaluation. This continuous feedback loop, driven by real operating data, is what makes AiOM® a living, adaptive system rather than a static compliance exercise.

Figure 2: AiOM® integrated framework—eight complementary disciplines operating as a unified, continuously improving integrity management system.

SECTION 04

Digital Transformation of AiOM®

From data collection to predictive intelligence

The fifth generation of asset integrity management is being shaped by a convergence of digital technologies that, when properly integrated with a rigorous engineering foundation, can transform what is possible. TCR Advanced Engineering is at the forefront of this transformation, helping clients deploy these technologies in ways that deliver genuine risk reduction rather than data proliferation.

Figure 3: Digital AiOM® architecture—a three-layer model integrating physical asset infrastructure, the AiOM® engineering framework, and digital intelligence technologies.

Digital twin integration

A digital twin is a continuously updated virtual replica of a physical asset, fed in real or near-real time by operating data, inspection findings, and condition monitoring measurements. For asset integrity, digital twins enable scenario modelling, remaining life simulation, and predictive risk assessment that static inspection databases simply cannot provide.

> **CAPABILITY**
>
> TCR Advanced Engineering builds integrity digital twins by integrating RBI risk profiles, FFS assessment results, corrosion rate models, and real-time process data. The result is a dynamic, continuously updated view of asset health across the entire plant—enabling proactive intervention days or weeks before a condition would appear on a conventional

> inspection schedule.

Machine learning for damage prediction

Traditional corrosion rate estimation relies on generic industry data and periodic manual measurements. Machine learning models trained on plant-specific corrosion monitoring data, process operating history, and inspection findings can predict damage rates with significantly greater precision, enabling more accurate remaining life estimates and more targeted inspection programmes.

- ML models can identify leading indicators of accelerated corrosion months before they register on conventional inspection readings.
- Correlation of process variables with corrosion rates enables proactive intervention when operating conditions trend toward higher-risk regimes.
- These methods are particularly powerful for CUI and under-deposit corrosion, where conventional inspection is inherently limited by accessibility.

IoT-enabled real-time integrity monitoring

Deployment of permanent corrosion monitoring sensors, online thickness measurement systems, and process data historians integrated with AiOM® platforms enables a shift from periodic to continuous integrity monitoring. Real-time data feeds directly into RBI risk models, enabling dynamic inspection intervals that respond to actual plant behaviour rather than static assumptions.

- Automated IOW alert systems notify integrity engineers within minutes of operating exceedances, enabling rapid response before damage accumulates.
- Permanent online UT probe systems on high-consequence circuits eliminate the need for periodic manual readings in hazardous or inaccessible locations.

Advanced NDE and drone/robotics inspection

Inspection technology has advanced dramatically. Phased Array UT (PAUT), Full Matrix Capture (FMC), Total Focusing Method (TFM), and Guided Wave UT (GWUT) provide inspection capabilities unavailable to earlier generations. Drone-mounted sensors and robotic crawlers enable inspection of previously inaccessible locations—live tanks, elevated piping, confined spaces—without scaffolding or shutdown.

> **2025 ADVANCEMENT: AI-ASSISTED NDE INTERPRETATION**
>
> AI-assisted interpretation of PAUT and TOFD datasets is reducing inspection time while improving defect detection sensitivity. Models trained on thousands of validated inspection

> datasets can flag indications for human review, reducing false negatives and improving consistency across different operators and time periods.

The hydrogen economy: new integrity challenges

The global transition to green hydrogen introduces a set of integrity challenges that the industry is only beginning to come to terms with. Hydrogen service introduces damage mechanisms—hydrogen embrittlement, hydrogen-induced cracking (HIC), and stress-oriented hydrogen-induced cracking (SOHIC)—that require specialised materials knowledge and inspection approaches distinct from conventional hydrocarbon service. Equipment qualified for natural gas service may require re-evaluation before hydrogen service.

- TCR Advanced Engineering's metallurgical depth positions us to support clients navigating the materials and integrity challenges of hydrogen service, from material selection to inspection technique qualification.
- AiOM® frameworks for hydrogen facilities must explicitly address hydrogen-specific damage mechanisms in CCDs, RBI assessments, and IOW definitions.

Cloud-based integrity management platforms

Consolidation of inspection data, RBI assessments, corrosion monitoring, and work order management on integrated cloud platforms enables cross-discipline and multi-site collaboration that was previously impossible. Inspection findings are immediately accessible to corrosion engineers; RBI profiles are available to turnaround planners; IOW exceedances auto-generate work orders in the CMMS. The result is a more responsive, more efficient integrity management system, and in our experience, a noticeable improvement in the quality of conversations between the people who own the assets and the people who maintain them.

SECTION 05

Attributes of a Successful AiOM® Programme

What separates the outstanding from the average

Not all AiOM® programmes deliver equal results. TCR Advanced Engineering has observed—and built—integrity management programmes across dozens of process facilities in India and the Middle East. Programmes that consistently deliver outstanding safety and business performance share a common set of attributes. They are worth describing plainly because, in our experience, they are not difficult to understand but are surprisingly difficult to install.

1. Quantitative performance metrics

The most effective AiOM® programmes are managed with quantitative KPIs, not qualitative assessments. Key metrics include overdue inspection percentage, RBI risk distribution trend over time, active bad actor count, IOW exceedance frequency, corrective maintenance as a share of total maintenance cost, and mean time between failures by equipment category. Without measurement, sustained improvement is impossible, and what is not measured tends, slowly, to become invisible.

2. Systematic digitisation

Data that lives in filing cabinets or disconnected spreadsheets cannot drive intelligent decisions. Successful AiOM® programmes digitise their complete inspection history, including pre-digital records, making it searchable, analysable, and actionable. This includes as-built drawings, corrosion monitoring data, and process historian data, all in a common digital environment.

3. Proactive bad actor programmes

A bad actor is equipment with disproportionately high maintenance cost, failure frequency, or safety risk relative to its peers. Systematic bad actor identification, followed by targeted root-cause improvement programmes rather than symptomatic repairs, has consistently delivered the highest-ROI maintenance initiatives in the process industry. A mature AiOM® programme maintains a living bad actor register with active improvement projects against every item on it.

4. Accessible, user-friendly systems

The most sophisticated AiOM® framework is worthless if operators, inspectors, and maintenance engineers do not engage with it daily. System usability is not a luxury; it is a prerequisite for effectiveness. Inspection reports must be accessible in the field on mobile devices. Risk visualisations must be intuitive. Data entry must be simple. The best programmes invest as much in change management and training as in technical content, and we have come to think of EvolvebyTCR, our training arm, as part of the same continuum.

5. Validated, current equipment inventory

An AiOM® programme is only as good as its equipment data. Many plants carry outdated inventories that do not reflect decades of modifications, additions, and retirements. Before any integrity initiative begins in earnest, a comprehensive equipment inventory validation, against as-built drawings, field walk-downs, and CMMS records, is essential.

6. Disciplined inspection schedule management

RBI generates inspection schedules that must be actively managed. Overdue inspection backlogs are among the most common findings in integrity audits, and among the most significant leading indicators of catastrophic failure risk. Successful programmes track schedule compliance with the same rigour as financial performance, with escalation protocols for approaching due dates and clear accountability for overdue items. We have learned, the hard way, that a quietly slipping inspection schedule is almost always the first warning of a quietly slipping programme.

SECTION 06

Critical Damage Mechanisms

The silent threats that conventional inspection programmes miss

A reformer tube that creeps for five years and then fails catastrophically is a manageable problem—if you know it is creeping. A CUI failure that occurs on a routine insulated line, never flagged in an inspection programme because the visible insulation looked intact, is a different kind of problem. It is a failure of imagination, not of inspection. The mechanisms below are the ones we see most often when imagination has run out.

Of all technical subjects in asset integrity, damage mechanism identification is the most consequential, and the most chronically underinvested. An RBI programme that misidentifies the active damage mechanism on a circuit is not just ineffective; it is actively dangerous, generating false confidence in inspections that cannot detect the actual threat. Three categories of damage are particularly prone to being underestimated or missed entirely.

Corrosion Under Insulation (CUI)

CUI is the single most prevalent cause of piping failures in process plants, responsible for an estimated forty to sixty per cent of all piping leaks in facilities over fifteen years old. The mechanism itself is unremarkable. Moisture penetrates damaged insulation, accumulates on the metal surface, and drives an electrochemical corrosion cell. The problem is that by definition the damage is invisible from outside, because the corroding metal is hidden under the very insulation that is supposed to protect it.

- Temperature ranges of greatest risk: -4°C to 150°C (25°F to 300°F) for carbon steel; chloride SCC risk extends to higher temperatures for austenitic stainless steel.
- Key vulnerability factors: age of insulation system, weather barrier integrity, historical water intrusion, cyclic temperature service, proximity to water sources such as cooling towers, steam traps, and deluge systems.
- Detection methods: Pulsed Eddy Current (PEC) screening, Guided Wave UT (GWUT) for long-range screening, profile radiography, and targeted insulation removal for high-risk locations.

CRITICAL FINDING

The majority of CUI failures occur on ‘routine’ insulated lines not identified as high-risk in traditional inspection programmes. The key differentiator in effective CUI management is a systematic, circuit-level susceptibility assessment, not ad-hoc inspection of visibly deteriorated insulation.

Small-bore piping (SBP) failures

Small-bore piping—typically NPS 2 inches and below—is disproportionately represented in process industry failures relative to its prominence in inspection programmes. Branch connections, deadlegs, instrument taps, and connection points are particularly vulnerable to corrosion, erosion-corrosion, and vibration-induced fatigue. Yet SBP is frequently excluded from RBI assessments on grounds of volume and perceived low consequence.

This exclusion is a false economy. Small-bore failures are a leading cause of hydrocarbon releases, fires, and environmental incidents. A dedicated SBP inspection programme, including systematic identification of deadlegs and susceptible connection geometries, is an essential AiOM® component, not an optional add-on.

Metallurgical degradation mechanisms

Several damage mechanisms gathered under the broad category of metallurgical degradation are particularly insidious because they often progress without visible symptoms, are not detectable with standard UT inspection, and can cause catastrophic brittle or sudden failures with minimal warning. These are the mechanisms for which metallurgical expertise is most critical, and the ones for which TCR Advanced Engineering has spent twenty-five years building proprietary microstructural databases.

- **High-Temperature Hydrogen Attack (HTHA).** Occurs in carbon and low-alloy steel in high-temperature, high-partial-pressure hydrogen service. Methane bubble formation at grain boundaries leads to fissuring and loss of ductility, with no external indication until catastrophic failure. Risk management per API 941 (Nelson curves) is essential. The mechanism is critical in hydroprocessing, reforming, and hydrogen production units, and is becoming increasingly relevant as the industry expands green hydrogen production and retrofits existing equipment.
- **Creep and Stress Relaxation Cracking (SRC).** Time-dependent deformation and cracking at elevated temperatures, particularly prevalent at welds in P91 and other creep-resistant steels used in power generation and high-temperature process service. Requires specialist metallurgical assessment of operating temperature history. Often underestimated in plants that have run sustained hours above design temperature.
- **Stress Corrosion Cracking (SCC).** Multiple forms—chloride SCC, polythionic acid SCC, caustic SCC, amine SCC—each requiring specific material, environment, and stress conditions to initiate. SCC can propagate to failure from a surface condition invisible to magnetic particle inspection. Active in fired heater tubes, heat exchanger bundles, and austenitic stainless steel piping.
- **Temper Embrittlement and Liquid Metal Embrittlement (LME).** Metallurgical degradation that reduces fracture toughness and increases the risk of brittle fracture at or near operating temperature. LME from liquid zinc or copper contamination can cause sudden, catastrophic failure with no prior indication. Must be specifically evaluated before startup of equipment that has undergone weld repairs or thermal modifications.

SECTION 07

The Metallurgical Imperative

Why no AiOM® programme is complete without metallurgical depth

If there is one conviction that has shaped TCR Advanced Engineering over twenty-five years, it is this: asset integrity management is, at its foundation, a materials science problem dressed up as an inspection problem.

Every damage mechanism—corrosion, cracking, embrittlement, creep—is governed by the interaction of material composition and microstructure with the operating environment and stress state. Yet metallurgical expertise is increasingly rare in process industry integrity teams, gradually displaced by inspection technicians whose expertise lies in measurement rather than mechanism. The result is plants that know precisely how much metal they have lost without knowing why they are losing it.

This gap is consequential. Inspection can detect damage; only metallurgical expertise can explain why it occurred, predict where it will occur next, and prescribe the correct remediation. The difference between a programme that generates inspection data and one that prevents failures lies in the quality of engineering interpretation applied to that data. It is also the reason that TCR's in-situ metallography programme—a discipline this firm helped establish in India—remains one of the most heavily relied-upon services we offer to long-running assets.

The roles of the metallurgical expert in AiOM®

- **Damage mechanism identification.** Identifying all active and credible damage mechanisms in each process unit, and screening for mechanisms that could activate with changes in operating conditions, feed composition, or future process modifications.
- **Root cause analysis.** Determining why specific failures occurred—connecting observed damage morphology to operating conditions, material properties, and design choices—so that the response is recurrence prevention rather than repeat repair.
- **Materials selection for life extension.** Evaluating whether existing materials of construction remain appropriate for the current and projected operating envelope, and recommending upgrades where the evidence warrants.
- **Fitness-for-Service.** Performing and critically reviewing FFS assessments that require understanding of fracture mechanics, creep behaviour, and environmental cracking susceptibility beyond standard API 579 calculations.
- **Emerging service environments.** Navigating the materials challenges of new service environments—hydrogen economy, carbon capture and sequestration, high-CO_2 processing—where conventional corrosion data is limited and expertise is scarce.

TCR ADVANCED ENGINEERING DIFFERENTIATOR

TCR Advanced Engineering combines process industry metallurgical expertise with advanced NDT capability under one roof, and backs both with NABL/ISO 17025 accredited material testing across chemical, mechanical, metallographic, and NDT disciplines. This integration—genuinely rare in our industry—means inspection findings are interpreted in real time by engineers who understand the underlying damage physics. The result is faster, more accurate integrity assessments that go beyond data collection to deliver engineering conclusions a plant manager can act on.

SECTION 08

TCR's Implementation Methodology

A proven fifteen-step approach to building a mature AiOM® programme

Implementing AiOM® is not a technology deployment. It is an organisational transformation. TCR Advanced Engineering's structured fifteen-step methodology builds an integrity management programme from the data foundation up, progressing systematically through the technical, digital, and organisational dimensions of a mature system. Each phase delivers demonstrable value before the next begins, which is how we keep the programme funded long enough to finish.

01

Digital Readiness Assessment

Evaluate current data systems, software infrastructure, and personnel capabilities. Establish baseline maturity against the AiOM® framework and identify gaps before implementation begins.

02

Equipment Inventory Validation

Validate completeness and accuracy of equipment registers against as-built drawings, P&IDs, and field walk-downs. Create the authoritative data foundation for all subsequent integrity work.

03

Corrosion Circuit Mapping

Define corrosion circuits for all pressure equipment, grouping equipment with similar damage mechanisms, materials, and process environments for consistent RBI treatment.

04

Damage Mechanism Assessment

Identify all active and credible damage mechanisms for each corrosion circuit, drawing on operational data, process chemistry, materials of construction, and operating history. This is the most technically demanding step, and the one where metallurgical expertise is most critical.

05

CCD Development

Develop Corrosion Control Documents for each process unit, capturing the full damage mechanism landscape, susceptible equipment, recommended inspection methods, and frequency guidelines.

06

RBI Assessment

Perform quantitative or semi-quantitative RBI assessments per API 580/581 for all pressure-containing equipment, generating risk-prioritised inspection plans with a defensible technical basis.

07

IOW Definition

Define Integrity Operating Windows for all critical process variables, establishing the safe operating envelope and the alert and critical response thresholds for each.

08

FFS Assessment for Known Anomalies

Perform FFS assessments per API 579-1/ASME FFS-1 for all known equipment anomalies to establish safe operating conditions and remaining life estimates for the next inspection period.

09

RCM / FMEA Analysis

Apply RCM methodology to rotating and static equipment to develop a maintenance programme aligned to actual failure modes and their business consequences, eliminating ineffective time-based tasks.

10

Bad Actor Identification

Systematically identify equipment with disproportionate maintenance cost, failure frequency, or safety risk, and initiate targeted root-cause improvement programmes for each.

11

Inspection Plan Development

Develop detailed, RBI-driven inspection plans specifying method, extent, and frequency for each equipment item, integrated with turnaround planning and outage scheduling.

12

Digital Platform Integration

Integrate RBI, inspection, corrosion monitoring, and process data on a unified digital platform. Configure IoT-enabled IOW alerts and real-time risk score updates where sensor infrastructure exists.

13

Digital Twin Development

Build integrity digital twins for the highest-risk and most critical process circuits, enabling scenario simulation, sensitivity analysis, and predictive risk assessment.

14

KPI Dashboard Implementation

Configure quantitative AiOM® KPI dashboards for management reporting, tracking overdue inspections, risk distribution trends, bad actor status, and IOW exceedance frequency over time.

15

Continuous Improvement Programme

Establish the governance cadence for ongoing AiOM® management—regular RBI review cycles, MOC integration protocols, RCA learning loop, and annual programme benchmarking against industry standards.

THE BOTTOM LINE

TCR's methodology is designed to deliver demonstrable value at every phase, not just at project completion. By the end of Phase 1 (Steps 1–6), clients already have a risk-prioritised inspection programme that outperforms their previous approach. By Phase 3 (Steps 12–15), they have a fully digital, continuously improving AiOM® system that is theirs to operate, not ours to depend on.

SECTION 09

Quantified Business Value

Measurable outcomes from a mature AiOM® programme

The business case for AiOM® is grounded in measurable operational outcomes that TCR Advanced Engineering has delivered for clients across the process industry. Organisations that implement AiOM® with discipline and engineering rigour achieve substantial improvements in equipment availability, maintenance efficiency, and process safety performance—consistently, reproducibly, and in our experience, within the first programme cycle.

Value Dimension	Typical Improvement	Primary Mechanism
Inspection Cost Efficiency	20–30% reduction	Risk-based prioritisation eliminates low-value inspections on low-risk equipment while concentrating resources on genuine threats.
Unplanned Shutdown Frequency	35–45% reduction	Predictive identification of developing threats enables planned intervention before catastrophic failure, eliminating most equipment-failure-driven unplanned shutdowns.
Equipment Availability	15–25% improvement	Optimised inspection and maintenance programmes reduce corrective maintenance frequency and duration, improving overall equipment effectiveness.
Maintenance Operating Cost	20–30% reduction	RCM eliminates ineffective time-based tasks; bad actor programmes address root causes; the planned-to-reactive work ratio improves substantially.
Turnaround Scope & Duration	15–25% reduction	RBI-driven scopes eliminate unnecessary equipment opening while ensuring risk-critical items are addressed, reducing both scope and duration.
Programme ROI	5:1 to 15:1 over 3 years	Risk-adjusted return on AiOM® investment—measured as avoided failures and unplanned shutdowns versus total programme cost—consistently exceeds 5:1 in the first three

Value Dimension	Typical Improvement	Primary Mechanism
		years.

The ESG value proposition

Beyond direct operational savings, mature AiOM® programmes deliver significant ESG value that is increasingly material to investors, regulators, and the communities in which process plants operate.

- ▸ **Process safety performance.** Systematic reduction in unplanned releases, fires, and process safety incidents, improving safety outcomes and reducing regulatory enforcement exposure.
- ▸ **Environmental performance.** Reduction in flaring events, hydrocarbon releases, and associated greenhouse gas emissions, directly improving carbon footprint metrics and environmental compliance.
- ▸ **Asset life extension.** Maximising the productive life of existing infrastructure rather than investing in new build, with significant embodied-carbon and capital-efficiency benefits aligned to net zero strategies.
- ▸ **Workforce safety.** Risk-informed scheduling and the use of drone inspection, remote monitoring, and robotic techniques reduce personnel exposure to hazardous inspection environments.

> **THE STRATEGIC CASE**
>
> Leading process industry operators increasingly view AiOM® not as a maintenance function but as a strategic capability—one that lets them operate assets harder, longer, and more sustainably than competitors relying on reactive maintenance. In a world of tightening capital, rising ESG expectations, and aging infrastructure, AiOM® programme maturity is a genuine and durable source of competitive advantage.

A WORD IN CLOSING

From Compliance to Confidence

An invitation to the operators of aging assets

If you have read this far, you are almost certainly one of two people. You are either an engineer who is tired of being asked to keep aging assets running on inspection budgets designed for younger plants, or you are a plant leader trying to work out how much of the digital-transformation language sweeping the industry is real, and how much is decoration. We wrote this paper for both of you.

AiOM® is our considered answer to a question we have spent twenty-five years thinking about. It is the framework we use ourselves, the framework we have refined across more than nine thousand investigations, and the framework that, in our honest assessment, gives the Indian and regional process industry the best chance of competing safely with the largest operators in the world. It is not the only good answer to the question of how to manage industrial assets in the fifth decade of their lives, but it is the answer that has worked for us, and for the operators who have trusted us with their plants.

Two convictions sit underneath everything we have written here. The first is that metallurgy is not optional. No quantity of digital twin or machine learning will save a programme that does not understand the damage mechanism on which it sits. The second is that data, on its own, is not intelligence. Intelligence is what happens when an engineer who knows the plant looks at the data and asks the right question of it. AiOM® exists to make sure that conversation happens, every day, on every circuit that matters.

If anything in this paper has been useful, or anything in it has been wrong, write to me. The address below reaches my desk. The best conversations in this industry happen one engineer to another, and the most expensive failures, in my long experience, are the ones nobody talked about before they happened.

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REFERENCES

References & Standards

API Standards

- API 580 (3rd Ed., 2016) — Risk-Based Inspection. American Petroleum Institute.
- API 581 (3rd Ed., 2016) — Risk-Based Inspection Methodology. American Petroleum Institute.
- API 579-1/ASME FFS-1 (2021) — Fitness-for-Service. American Petroleum Institute / ASME Joint Publication.
- API 584 (2014) — Integrity Operating Windows. American Petroleum Institute.
- API 970 (2018) — Corrosion Control Documents. American Petroleum Institute.
- API 941 (9th Ed., 2016) — Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants.

International Standards

- BS 7910:2019 — Guide to methods for assessing the acceptability of flaws in metallic structures. BSI Standards.
- ISO 55000:2014 — Asset management — Overview, principles and terminology. International Organization for Standardization.
- ISO 55001:2014 — Asset management — Management systems — Requirements. ISO.

Reliability Standards

- SAE JA1011 (1999) — Evaluation Criteria for Reliability-Centered Maintenance (RCM) Processes. SAE International.
- SAE JA1012 (2002) — A Guide to the Reliability-Centered Maintenance (RCM) Standard. SAE International.

Industry Publications & Research

- Solomon Associates (2024) — Fuels Study: Refinery Performance Benchmarking. Solomon Associates Ltd.
- AMPP (2024) — Corrosion Under Insulation: Detection and Prevention Best Practices. Association for Materials Protection and Performance.
- UK Health and Safety Executive (2021) — Improving maintenance, inspection and testing in major hazard industries.
- McKinsey & Company (2023) — Operational Excellence in Asset-Intensive Industries: The Digital Transformation Opportunity. McKinsey Global Institute.
- Boston Consulting Group (2024) — Unlocking the Full Potential of AI in Asset Management. BCG Henderson Institute.

TCR Advanced Engineering Technical Publications

- TCR Advanced Engineering (2024) — Advanced NDE Techniques for CUI Detection: A Comparative Field Study.
- TCR Advanced Engineering (2024) — High-Temperature Hydrogen Attack: Detection, Assessment, and Risk Management in Hydroprocessing Units.
- TCR Advanced Engineering (2025) — Integrity Management for Hydrogen Service: Emerging Damage Mechanisms and Engineering Solutions.
- TCR Advanced Engineering (2025) — Digital Twins for Asset Integrity: A Practitioner's Framework for Implementation.

ABOUT THE FIRM

About TCR Advanced Engineering

TCR Advanced Engineering Pvt. Ltd. was founded in 1999 as the materials testing, advanced NDT, and engineering consulting arm of the TCR Group, which was itself established in 1973. The combined heritage gives the firm more than fifty years of group expertise in metallurgical investigation, asset integrity management, and industrial diagnostics.

Headquartered at GIDC Makarpura, Vadodara, Gujarat, TCR Advanced operates NABL/ISO 17025 accredited laboratories across chemical, mechanical, metallographic, and non-destructive testing disciplines, holds Nadcap accreditation for Materials Testing (AC7101/3, /4, /5, /14), and is approved by the Central Boilers Board (CBB) for inspection of Indian Boiler Regulation (IBR) equipment. The firm serves more than 1,700 clients across 18 industries, including major oil and gas operators, refineries, petrochemical plants, power utilities, fertiliser producers, and EPC contractors.

TCR Advanced's service architecture rests on four pillars: engineering consulting (Fitness-for-Service, Remaining Life Assessment, failure investigation, corrosion engineering, and AiOM® programme delivery); advanced NDT (PAUT, TOFD, AET, helium leak testing, infrared thermography, in-situ metallography); conventional NDT (UT, RT, MT, PT, VT, ET, PMI); and material testing (mechanical, chemical, metallographic, civil and concrete). Together with EvolvebyTCR, the firm's engineering training academy, this architecture covers the full lifecycle of asset integrity, from initial qualification through end-of-life decision-making.

The firm is led by Managing Director Paresh Haribhakti, a metallurgical engineer with a postgraduate degree in Materials Technology from M.S. University of Baroda. He is the co-author of the ASM International publication on boiler tube failure investigation (2018) and a contributing author to ASM Handbook Volume 11A (2021). He speaks regularly at national and international conferences on failure analysis, integrity management, and the role of digital intelligence in industrial reliability.

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Service taglines

Engineering Consulting · *Precision decisions for complex assets.*
Advanced NDT · *See what others cannot detect.*
Material Testing · *Every result you can defend.*
AiOM® · *Where metallurgy meets the digital future.*