2025 | VOLUME 55

SI SOLUTIONS™

NEWS & VIEWS

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CEO Message

MARK W. MARANO
President and CEO
mmarano@sisolutions.com

As I enter my sixth year as CEO, it is remarkable to reflect on how much SI Solutions (SI) has evolved and grown. In my message last year, I discussed the successful integration of SC Solutions and our transition from three independent companies to six distinct business units, each driving advanced engineering, specialty services, and digital solutions across critical industries. In August 2024, we took the next step in our evolution when SI was acquired by MidOcean Partners.

This new partnership represents more than just a change in ownership - it's an acceleration of our long-term strategy. Since 2019, the combined revenue of SI's member companies has grown by 60%, fueled by our commitment to technical excellence, problem-solving, and industry leadership. MidOcean's investment strengthens this trajectory, providing capital, flexibility, and strategic expertise to expand our capabilities through organic growth and targeted acquisitions. Most importantly, our leadership team and business structure remain intact, ensuring stability for our employees and clients as we continue to broaden our offerings and impact.

Following the acquisition, the senior leadership of our six business units, the executive team, and several board members met at our Denver office for a September planning meeting. The discussion was highly strategic, focusing on how the industries we serve are changing, what we are currently doing to support them, and how we can adjust and invest to ensure we continue providing the services our clients want and need.

This momentum comes at a pivotal time for the industries we serve. Nuclear power is experiencing a true resurgence, one that feels fundamentally different from the so-called "Nuclear Renaissance" I witnessed firsthand at Westinghouse years ago. Today, we see broad bipartisan support alongside innovative technology deployments, life extensions of existing plants, and the acceleration of advanced reactor designs. SI Solutions is uniquely positioned to support these developments, providing expertise from new plant design and licensing to life extension strategies and optimization of daily operations. This edition features six articles highlighting a portion of our nuclear expertise supporting this resurgence.

- Plant Improvements / Updates: As plants pursue life extensions and power uprates, they are investing significant capital in equipment upgrades. Our feature on **large equipment replacements** details how SI's structural capabilities support safe and efficient heat exchanger upgrades, while our **cathodic protection** case study highlights a first-of-its-kind system implementation in response to SLR commitments.
- Cost Optimization: Strategic chemistry solutions, such as **resin optimization**, demonstrate how SI can help extend resin lifespan and reduce long-term operating costs.
- Long-Term Asset Management: our **life-cycle management** article summarizes best practices for extending the lifespan of raw-water piping and optimizing risk-based asset management.

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Beyond nuclear, broader market trends reinforce the need for life extension, reliability, and resiliency across the energy sector. Our clients are modernizing aging infrastructure to keep pace with growing power demands, evolving regulations, and emerging technologies. SI is providing critical expertise to meet these challenges head-on, as demonstrated in the articles below.

- A feature on a **just-in-time winterization** effort conducted by our Process Industries group, supplying instrumentation and electrical (I&E) engineering and construction at a large petrochemical facility in Texas.
- A summary of lessons learned for long-term management of **high energy piping** systems, conveying the importance of an integrated approach that balances engineering and NDE.
- Best practices for recovery from **catastrophic component failures**, including a case study on the root cause analysis of a major **steam turbine failure**.

As we continue to grow, our ability to develop and deliver innovative solutions remains at the core of our success. This edition's article on **tank inspections** highlights several technological breakthroughs – leveraging advanced robotics and non-intrusive testing to improve inspection efficiency and accuracy while our **digital twins** article, developed by our Controls Engineering team, explores the onset of real-world applications for predictive, model-based artificial intelligence for asset management applications. Finally, our Pipeline Integrity team just released a web-based version of our **APTITUDE flaw evaluation software**, which supports the efficient evaluation of flaws identified during inline inspections.

To ensure SI remains responsive and retains our position as technical experts and innovators as we grow, we are executing an aggressive hiring plan for 2025, with 50+ new positions across our businesses. These new engineering and technical staff are resources that expand SI's expertise and allow us to better serve clients in all aspects, including peak period and emergent situation support. If you know of someone who may be interested in a career at SI, now is an excellent time for them to visit our careers page to explore open opportunities!

Finally, this issue represents a slight change to the News & Views format. In addition to a new look, we're shifting to an annual print issue with quarterly digital releases, helping us remain agile and provide relevant insights on technical innovations and industry trends as they emerge. Please subscribe to our digital distribution or follow us on LinkedIn to ensure you receive the latest updates.

The future of SI Solutions has never been brighter as we continue to evolve, grow, and strengthen our capabilities to support our clients for the long term. Thank you for your support, which enables us to fulfill our mission: powering the future of critical infrastructure.

Mark

PETER CONNOLLY JOINS SI AS CHIEF FINANCIAL OFFICER

Peter joined SI in January 2025, bringing over 20 years of corporate finance and operations experience. Prior to SI, he served in various executive finance roles for several utility infrastructure contractors. We are excited to have Peter on board to help grow the company while maintaining a strong fiscal foundation. His broad skill set, passion and leadership represent a critical change to the role.

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In this Issue

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Replacement of Large Equipment in Nuclear Power Plants

With many U.S. nuclear plants having extended operation well beyond their original licensed life, it is necessary to replace certain critical process components (e.g., large pumps, turbine rotors, heat exchangers). In many cases, equipment manufacturers are asked to provide larger, heavier equipment to deliver higher output and improve efficiency. Prior to installation, the existing structure must be evaluated for the larger static loads as well as one-time loads applied during movement (transit and rigging). SI has successfully collaborated with owners, design engineers, equipment manufacturers, and installation contractors to ensure safety and minimize disruption during this process.

JULIO GARCIA, PhD, PE
jgarcia@structint.com

NATALIE DOULGERAKIS, PE, SE
ndoulgerakis@structint.com

DAN PARKER, PE
dparker@structint.com

LACHEZAR HANDZHIYSKI
lhandzhiyski@structint.com

The U.S. power grid continues to benefit from the extended operation of traditional nuclear power plants, most of which began operation between 40 and 55 years ago. Due to unprecedented market demand, many plant owners are actively pursuing extended operating licenses (subsequent license renewal or SLR), and increased thermal and electrical power output (extended power uprate or EPU). Whether due to normal aging or increased performance demands, many plants are facing the challenge of replacing large pieces of original equipment (e.g., pumps, turbine rotors, heat exchangers) embedded deep within the facility. In many cases, sites are requiring larger and heavier replacement equipment to provide improved efficiency or additional margin.

THE CHALLENGE

Frequently, the initial structural design of these facilities typically did not explicitly account for replacement of certain large equipment (e.g., feedwater heaters, moisture separators, etc.). The removal, hauling, sliding, jacking, and installation of replacement equipment are new tasks that introduce significant operational and structural demands on the building structures as well as challenges to plant staff. High-demand loads may be temporarily imparted to building structures that were optimized during their original design based on original equipment and operations loads with limited strength margins. Re-evaluation of the building structure under the new, larger service loads is required, typically including gravity, seismic, wind, piping, and thermal loads. Particularly challenging and sometimes overlooked are new thermal loads imposed on the gravity load-resisting system of the building. These loads are the result of thermal deformations within the equipment piece itself or within other mechanical attachments, such as piping system that connects to it. Rigorous analyses are performed where there are complex networks of such attachments. Where multiple attachments connect to an equipment piece, it is key to combine the loadings at each attachment location in a conservative, yet realistic manner, to safely demonstrate structural adequacy.

SI has a proven track record of overcoming these challenges by applying rigorous structural analysis, optimizing retrofit strategies, and leveraging multi-disciplinary collaboration to limit disruption and minimize costs.

SI'S ROLE

Structural Integrity (SI) has provided key consulting services to support the replacement of large equipment for SLR and EPU, including moisture separator reheaters (MSRs) and feedwater heat exchangers (FWHs), among others. Working both as task leads, as well as independent reviewers, SI staff have successfully collaborated with owners, design engineers, equipment manufacturers, and installation contractors to safely replace large equipment. SI has provided key consulting related to technical and operational issues, helping to minimize disruption. Additionally, SI has provided a holistic approach that considers the benefits and challenges associated with use of different standards and methodologies to assess and potentially retrofit building structures designed and licensed many decades ago. As a result, SI structural engineers have been praised for providing significant contributions to optimize the process and minimize costs.

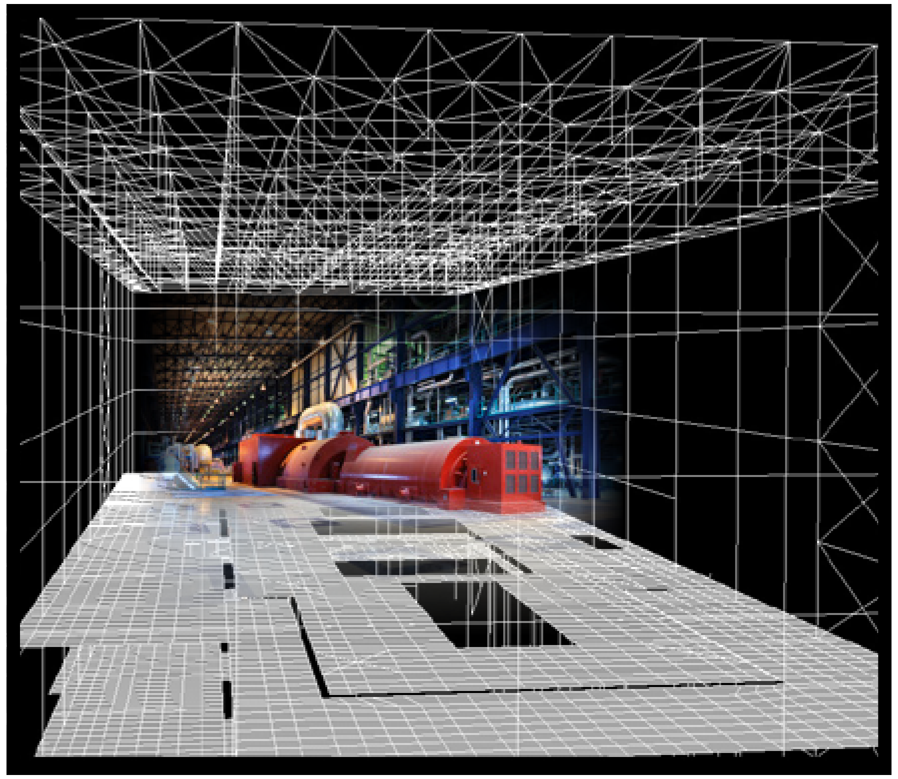

FIGURE 1. Operating Deck of a turbine building.

KEY SOFTWARE FOR STRUCTURAL ASSESSMENTS

Used for structural analysis and design, **GTSTRUDL** helps evaluate framing systems and load distribution under gravity, seismic, and equipment-induced forces.

A general-purpose structural analysis tool, **SAP2000** assesses floor framing response to new equipment loads, ensuring existing structures can accommodate changes safely.

A high-fidelity FEA tool, **ABAQUS** models localized stress, thermal effects, and nonlinear interactions, providing detailed results in highly-stressed regions to maximize available structural margins.

Piping Analysis
Used to evaluate thermal, pressure, and mechanical loads applied to large stationary components, piping analysis software ensures system integrity and compliance with applicable codes (e.g., ASME B31.1). SI utilizes **PIPESTRESS**, **AutoPIPE**, and **CEASAR II** for these evaluations, depending on application needs and/or designer preferences.

PROJECT EXAMPLE 1
(1,158 MW 4-LOOP PWR)

In support of the planned MSR replacement, SI developed 3-dimensional finite element models of the MSR units and their support frames, as well as the framing at the operating floor of the turbine building.

- Assessed combinations of pipe dead and thermal loads acting at MSR nozzle attachment locations to determine the most critical loading condition on the support frames and floor framing.
- Performed stress analysis of support frames to evaluate structural elements, welds, and bolted connections using ABAQUS.
- Performed structural evaluation of floor framing using SAP2000.
- Calculated framing member and connection capacities using the provisions of AISC 360 and ACI 318.

SI evaluated all structural elements within the MSR load path and confirmed the structure's adequacy to resist the demands given the design loads provided by the plant staff. The result: SI's recommendations and selected approach led to no structural retrofits being required of the turbine building, thus ensuring the planned operation was safe to perform while saving the unnecessary expense of reinforcing the structure.

PROJECT EXAMPLE 2
(1,220 MW 4-LOOP PWR)

SI acted as the Owner's engineer and performed an independent review of the MSR replacement project, including a review of the structural analysis of the turbine building under the installation and operation of the new and heavier MSRs, as well as the proposed structural retrofits.

- Independent review of the turbine building analysis methodology and numerical model in GTSTRUDL software.
- Review of loading and requirements data from design basis criteria, calculations, licensing commitments, manufacturer information and transport/hauling information.
- Verification of loading data in GTSTUDL model.
- Assessment of structural member capacity results from GTSTRUDL model.
- Performance of independent calculations for steel-reinforced concrete composite section capacities.
- Provided recommendations on the analysis methodology, loading data and applicable design standards to optimize the strength margins of the existing turbine building.

Through an independent review of the MSR replacement project, SI demonstrated unrealized structural margin, reduced the number of structural retrofits to support the heavier MSR units, and provided recommendations on licensing strategy for the review and approval of the structural modifications supporting the MSRs replacement.

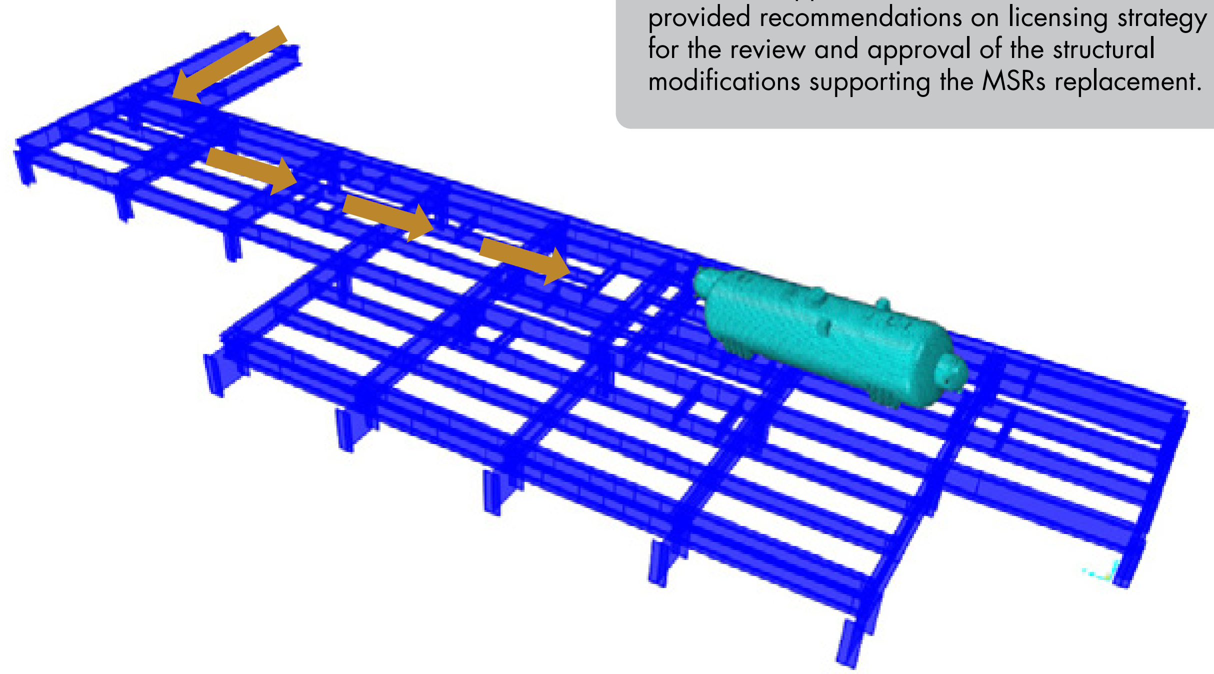

FIGURE 2. Sliding and Replacement of a Moisture Separator Reheater.

Cathodic Protection for SLR: Lessons Learned from System Implementation

CURTIS STRAUSS
cstrauss@structint.com

ISAAC HALL
ihall@structint.com

SI was engaged to design, install, and commission a site-wide impressed current cathodic protection (ICCP) system for the Turkey Point Nuclear Generating Station (PTN) to meet the site's ongoing subsequent license renewal (SLR) commitments. Prior to its SLR application, PTN did not have a cathodic protection (CP) system for buried piping; designing and installing an all-new ICCP system at this legacy facility posed unique challenges and required more support than a typical refurbishment project. This article summarizes the site-specific requirements, challenges and adjustments made by SI as part of our project methodology, which resulted in the first large-scale CP implementation for a nuclear site pursuing SLR.

Cathodic protection is an electrochemical technique used to prevent corrosion in buried or submerged metal structures [1], such as pipelines and storage tanks. It works by applying an electrical current to shift the metal's potential (voltage) relative to its soil environment, effectively halting corrosion. While CP is widely used, its application in dense station environments (such as nuclear power plants) is complicated by the network of interconnected metallic systems, grounding grids, and safety-related piping. These factors create electrical discontinuities and interfere with current distribution, requiring a tailored, iterative approach to ensure effective protection.

REGULATORY BASIS FOR CP IN NUCLEAR PLANTS

Guidelines for applying CP for the protection of buried piping in nuclear plants are outlined in the NRC's GALL-SLR report [2], specifically within Aging Management Program (AMP) XI.M41. This program defines preventive measures to mitigate external corrosion and establishes criteria for evaluating CP system effectiveness. The primary criterion requires achieving a polarized potential of -850 mV relative to a copper/copper sulfate electrode (CSE), measured using an "instant-off" technique to eliminate IR drop error [3].

While the -850 mV threshold is widely used, it can be impractical in complex plant environments due to factors such as high soil resistivity and extensive buried infrastructure. The GALL-SLR allows for alternative criteria – such as demonstrating at least 100 mV of CP polarization – provided the program incorporates additional verification methods for the most corrosion-susceptible piping materials (see Figure 1). Corrosion rate monitoring (CRM) is one such method, providing direct, real-time data on material loss trends to validate CP effectiveness.

For existing sites implementing large-scale CP systems for the first time, the GALL-SLR acknowledges that achieving full compliance may require iterative design modifications and use of multiple criteria. Regardless of approach, plants must demonstrate that the system provides effective protection over time, either by meeting voltage-based criteria during periodic surveys or by confirming that corrosion rates remain within acceptable limits (e.g., via CRM). Presence of effective CP reduces the number of direct inspections, minimizing the effect to ensure aging is managed within the AMP's regulatory framework.

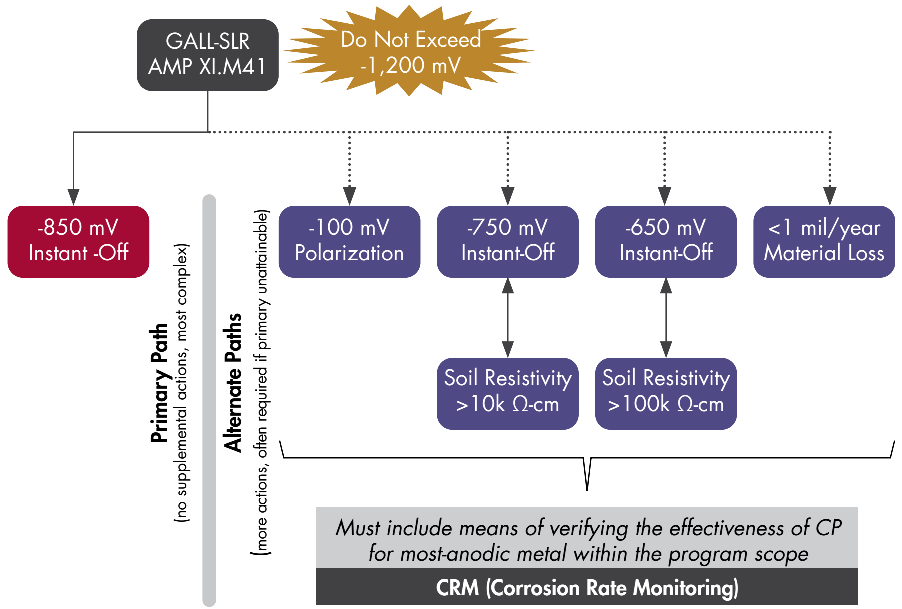

FIGURE 1. CP System Acceptance Criteria for Steel Materials

TURKEY POINT PROJECT OVERVIEW

In March 2021, SI was engaged by NextEra Energy (NEE) to design, install, and commission a site-wide ICCP system at the Turkey Point Nuclear Generating Station (PTN) to meet the commitments in NEE's SLR application. PTN was the first U.S. nuclear plant to be granted an SLR license, extending its operating life to 80 years. However, prior to this project, the site lacked a CP system for buried piping, making the design and implementation of an entirely new system a significant undertaking.

The primary objective was to provide effective CP for two key buried piping systems—Fire Protection (FPS) and Intake Cooling Water (ICW)—in accordance with AMP XI.M41 requirements. However, this project posed several unique challenges, such as:

- **Electrical discontinuities** in the non-welded FPS piping and between buried pipe and above-ground appurtenances.
- A **complex, congested** network of buried metallic systems and grounding infrastructure.
- **Limited access** to critical piping sections, particularly for the ICW system.
- An **aggressive project schedule,** driven by SLR commitments.
- **Rigid AMP commitments**, employing the most-conservative criterion (-850 mV) without consideration of site-specific requirements.
- **Geological constraints**, which increased the difficulty of drilling and precluded the use of deep anode groundbeds.

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To address these challenges, SI and its CP subcontractor, Bass Engineering, took an iterative approach to system design, installation, and commissioning. This process required multiple design refinements and targeted adjustments to achieve compliance with CP effectiveness criteria while navigating site-specific constraints. The following sections outline the overall CP implementation process and examine key challenges encountered at PTN, along with the solutions developed to address them.

GENERAL CP IMPLEMENTATION PROCESS

SI follows a structured process for large-scale CP projects, enabling adaptation to site-specific challenges while minimizing uncertainty and maintaining schedule adherence. These phases are outlined below.

PROJECT-SPECIFIC CHALLENGES AND OPTIMIZATION

The design and installation of an ICCP system at PTN presented multiple challenges due to tight project timelines, complex site infrastructure, and unique environmental conditions. SI employed the process shown below to achieve a successful implementation, through an iterative approach that allowed for refinement throughout the design, implementation, testing, and acceptance stages.

Project Timeline and Execution Constraints

The PTN CP implementation was constrained by a strict 18-month timeline, driven by commitments made to the NRC during the Subsequent License Renewal Application (SLRA). The project schedule was particularly demanding because Turkey Point had never previously installed a CP system for its buried piping. Unlike a CP refurbishment—where existing system data can be leveraged—this required a full site assessment, design, installation, and commissioning from scratch.

To stay on schedule, SI and its partners had to prioritize design-phase activities, focusing early efforts on:

- Assessing electrical continuity in the fire protection system (FPS), which was suspected to have discontinuities.
- Planning logistics for deep anode and shallow distributed groundbeds, given space and geological constraints.
- Collecting buried piping data for modeling and system layout.

1. **Initial Assessment and Planning**
   Site evaluation, environmental considerations, and corrosion risk analysis to establish project scope and key design inputs. Determination of structure or structures to be protected.
2. **Engineering Design and Equipment Specification**
   Iterative phase includes initial current requirement calculations and determination of system type / configuration (e.g., galvanic vs. ICCP, distributed vs. remote). Development of system layout, selection of materials and components (e.g., anodes, rectifiers, cables, bonding locations), and approximation of current distribution. May also include evaluation of cost and feasibility.
3. **Field Implementation**
   Installation of CP system infrastructure, including anode groundbeds, power feeds, connections to target structures, and CP test equipment (i.e., test stations).
4. **Initial Testing and Evaluation**
   System energization, validation of electrical continuity or isolation, baseline testing, and rough balancing based on field data.
5. **System Optimization**
   Refinement of system parameters and final balancing of rectifier outputs to achieve maximum performance. If initial testing identifies performance gaps, additional modifications may be required (e.g., isolation bonding, additional groundbeds, etc.).
6. **Ongoing Maintenance and Updates**
   Routine system monitoring, annual CP surveys, and any program-specific testing to confirm continued effectiveness. Adjustments and corrective actions are implemented as needed.

Despite efforts to streamline the process, some design phases were compressed compared to typical CP projects. This meant that certain design inputs—such as soil resistivity and total buried surface area—were estimated rather than measured directly. These unknowns contributed to gaps in the initial design, requiring later modifications to meet system performance requirements.

Even with these challenges, SI and its partners successfully delivered the first large-scale ICCP system for an SLR-licensed plant on time. However, the accelerated timeline meant that some early assumptions had to be revisited during implementation, leading to iterative system refinements.

Complexity of Existing Infrastructure

A significant challenge in implementing CP at PTN was the highly congested underground environment. The plant's buried infrastructure included a mix of metallic systems, grounding grids, and safety-related piping, many of which were electrically interconnected in unpredictable ways.

A critical issue was the electrical discontinuity within the FPS piping system, which used non-welded, mechanically joined ductile iron piping. These joints do not always provide reliable electrical continuity, resulting in sections of piping that were unintentionally isolated from CP protection. This posed a risk of stray current corrosion, where unprotected pipe segments could experience accelerated metal loss instead of protection.

Further complicating the design, the station's grounding grid was assumed to be continuous across the site. However, post-installation testing revealed that grounding connections varied significantly, leading to unexpected current distribution issues. This misalignment required additional continuity bonding and negative rectifier connections to improve current return paths and prevent stray current interference.

Additionally, gaps in design input—such as undocumented fire protection piping—led to errors in estimating total CP current demand. The system was initially undersized, requiring supplemental anodes and rectifier output adjustments to compensate.

Site-Specific Installation Challenge

Beyond electrical complexities, the physical installation of the ICCP system was complicated by Turkey Point's geology. The original CP design included deep anode groundbeds, but porous limestone formations created drilling difficulties that exceeded expectations.

During installation, drill crews encountered subsurface voids, which resulted in:

- Frequent drilling fluid loss, making borehole stabilization difficult.
- Equipment failures, increasing installation delays and costs.
- Higher-than-anticipated resistivity variations, affecting CP current distribution.

To mitigate these risks, SI and its partners modified the deep groundbed design, reducing borehole depth from 300 ft to 150 ft while increasing the number of anodes per groundbed. This adjustment maintained CP coverage while improving constructability.

Another major challenge was physical space limitations. The plant's discharge side had minimal room for CP infrastructure, requiring customized rectifier placement and cable routing. In some cases, anode locations had to be shifted or replaced with alternative CP methods to accommodate space constraints.

FIGURE 2. Groundbed Installation in the Radiological Area

FIGURE 3. Rectifier Operating in Plant Protected Area

CP System Performance and Optimization

One of the most significant project challenges was meeting the rigid acceptance criteria defined in PTN's SLRA commitments. While the GALL permits flexibility in CP effectiveness criteria – including a 100 mV polarization shift alternative – PTN initially committed to the most conservative threshold, requiring -850 mV polarized potential at all monitored test locations.

During initial commissioning, early test results revealed that meeting this standard was not technically feasible due to:

- Higher-than-expected soil resistivity, which limited CP current flow.
- Greater-than-estimated buried metallic surface area, significantly increasing CP output demand.
- Electrical discontinuities and grounding grid separation, disrupting uniform current distribution.

To address these issues, SI and its partners implemented an iterative optimization strategy, including:

- Installing additional dedicated test stations with corrosion rate monitoring (CRM) hardware to directly measure local corrosion rates.
- Rebalancing rectifier outputs to improve current distribution.
- Installing additional continuity bonds to mitigate electrical discontinuities.
- Adding three supplemental deep anode groundbeds, increasing overall CP current capacity.

Even with these modifications, it was clear that full compliance with the -850 mV criterion was neither practical nor necessary for effective corrosion prevention. SI and NEE initiated a licensing amendment process to adopt the 100 mV polarization shift criterion, while utilizing the CRM data as an independent verification method to confirm CP effectiveness.

The optimization process was executed in multiple phases, beginning in late-2022 and concluding in early-2024. Throughout implementation, progress toward the 100 mV criterion was verified through site-wide "annual" CP surveys, conducted at key milestones. Figure 4 illustrates the survey results overlaid on a map of the plant and target piping systems, while Figure 5 shows the progression of system improvements at each step in the optimization process. Additionally, CRM data confirmed that actual corrosion rates were well within acceptable limits (less than 1 mil / year), further validating that the CP system provided adequate protection – even in areas where 100 mV polarization was not fully achieved.

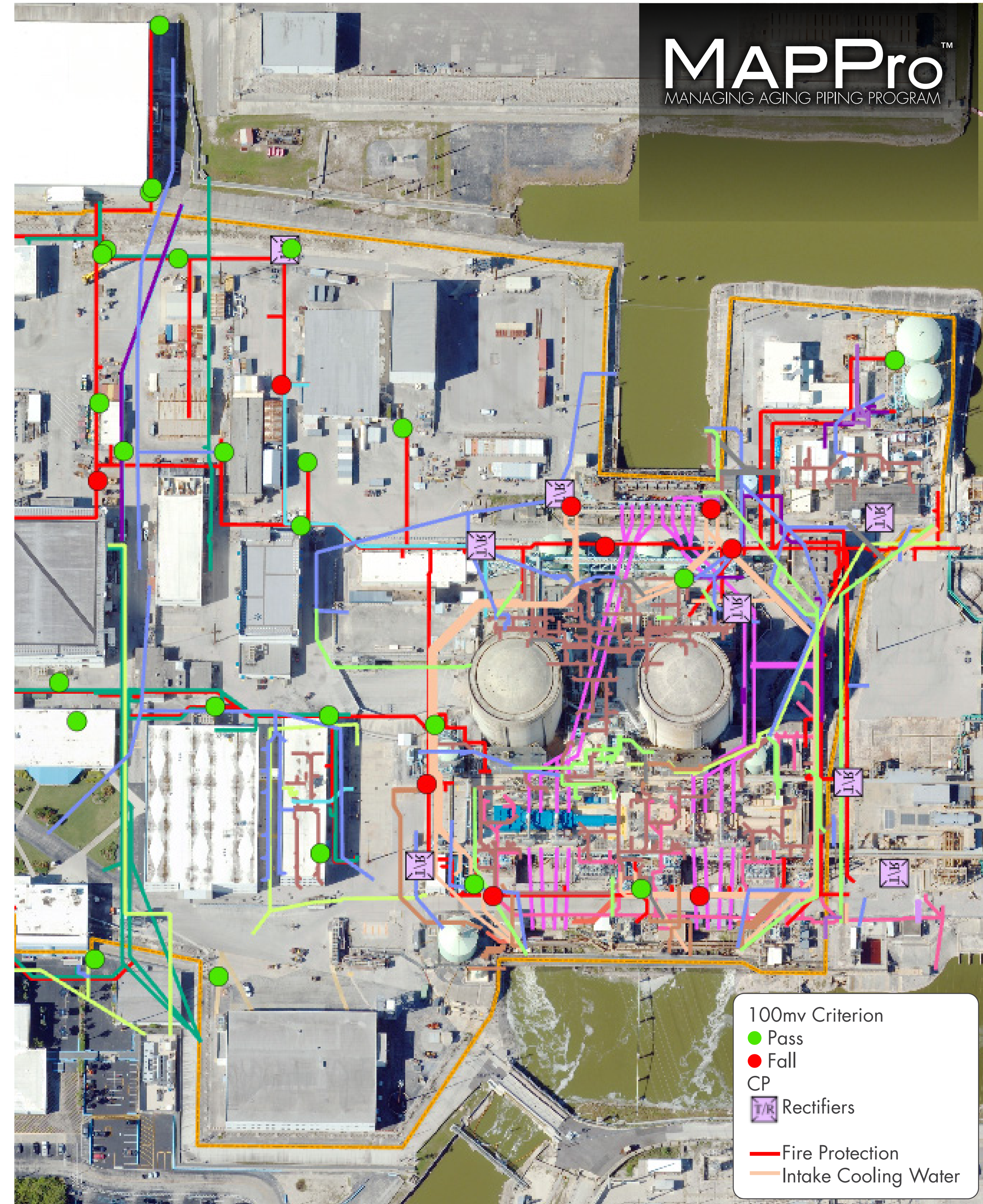
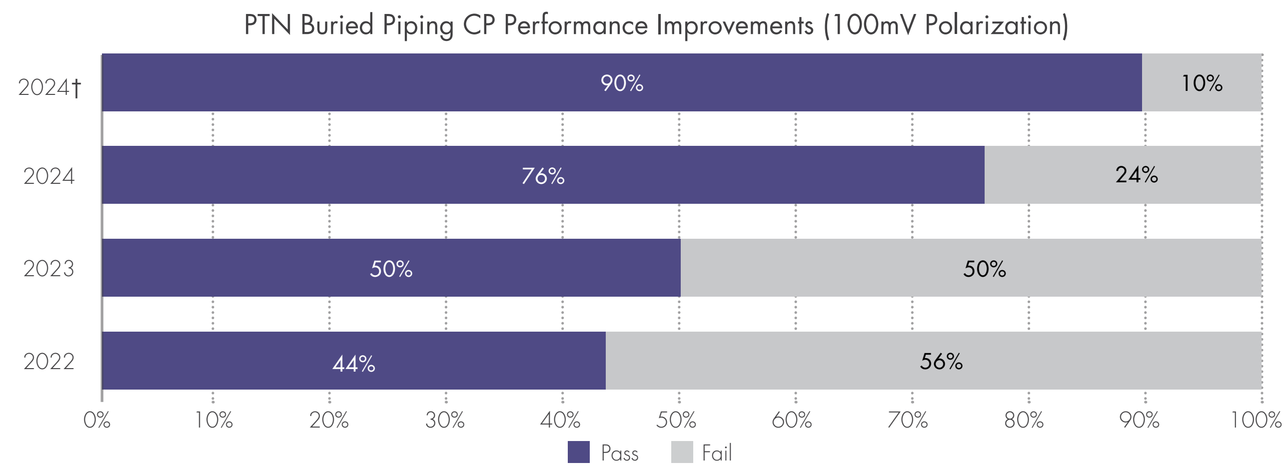


FIGURE 4. CP System Overview and Performance Assessment



†2024 Final Annual Survey results including updated readings obtained in October 2024 following the final round of bond installation and system balancing efforts.

FIGURE 5. CP System Performance Improvements from Optimization Effort

CONCLUSION

The implementation of a full-scale ICCP system at PTN marked a significant milestone, both for the site and for the nuclear industry's approach to management of aging piping under SLR. As the first U.S. nuclear plant granted an SLR license, PTN's CP system had to be designed and implemented from the ground up, introducing challenges that ranged from electrical discontinuities and geological constraints to strict licensing commitments and a compressed project timeline.

Through an iterative approach, SI and its partners were able to navigate these challenges while refining system performance. Early assumptions—particularly regarding electrical continuity, system grounding, and total CP current demand—required ongoing adjustments, including design modifications, additional bonding, and increased CP capacity. By leveraging corrosion rate monitoring (CRM) as an alternative assessment method, the team successfully demonstrated that the system provided effective protection, even when compliance with the original -850 mV criterion was impractical.

The PTN project provides key lessons for CP implementation at other nuclear facilities, particularly for sites transitioning to long-term aging management strategies. These insights are summarized in the box below. As other plants implement SLR AMP strategies for long-term buried piping protection, the experiences gained at PTN will help guide more efficient, flexible, and technically sound CP implementation.

KEY TAKEAWAYS

This project demonstrated that from-scratch, large-scale CP implementation in response to SLR-commitments requires flexibility and iteration.

- Regulatory commitments should be made with practical implementation in mind, considering alternative performance criteria where appropriate.
- Design assumptions must be verified early to avoid later rework.
- Geological constraints should be factored into deep groundbed feasibility before finalizing the design.
- Electrical continuity must be tested across all metallic systems to prevent isolation issues.

Through a structured yet adaptive approach, SI successfully delivered an effective ICCP system, balancing design compliance, site constraints, and long-term system maintainability.

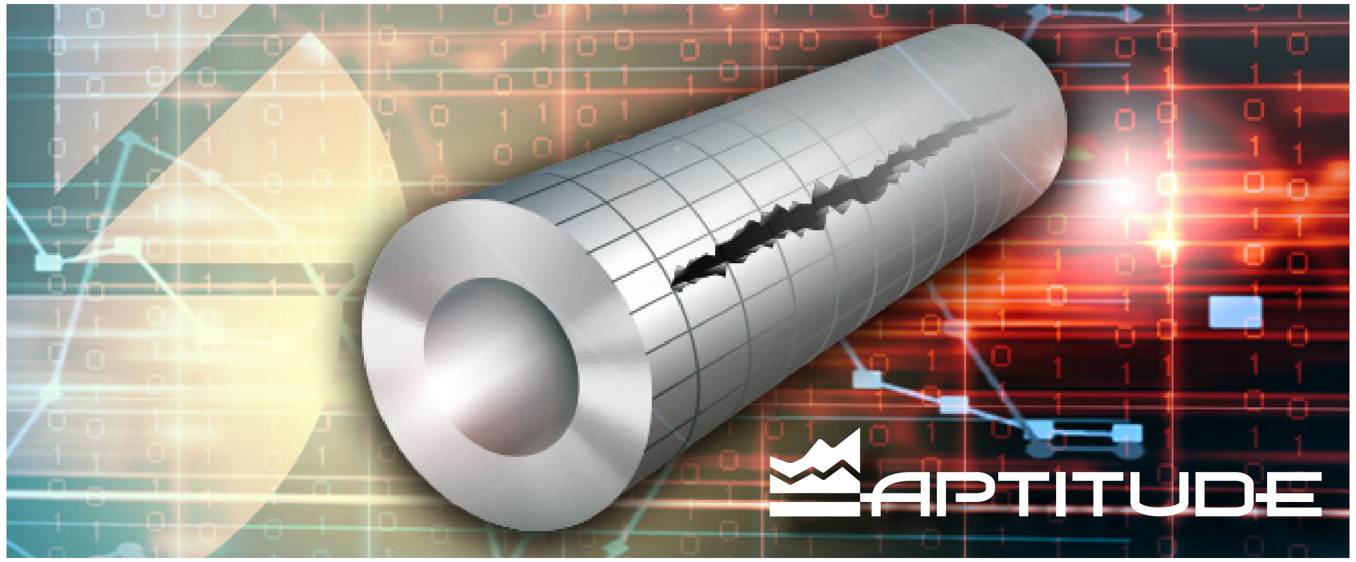
References

[1.] Luciano, Lazzari and Pietro, Pedeferri. Cathodic Protection. Milan : Polipress, 2006.

[2.] NRC. NUREG-2191 Generic Aging Lessons Learned for Subsequent License Renewal (GALL_SLR) Vol. II. Washington, D.C. : U.S. Nuclear Regulatory Commission, 2017.

[3.] SP0169 Control of External Corrosion on Underground or Submerged Metallic Piping Systems. Houston : NACE International, 2013.

Joint Industry Project: APTITUDE Flaw Evaluation Software



SCOTT RICCARDELLA
sriccardella@structint.com

TJ PREWITT
tprewitt@structint.com

TYSON MANNING
tmanning@structint.com

ISAAC SMITH
Ismith@structint.com

Aging pipeline infrastructure and past incidents have driven PHMSA to introduce stricter regulations, requiring operators to conduct rigorous evaluation of flaws identified during inspections. Recognizing these needs, SI developed APTITUDE, an analytical tool for calculating Predicted Failure Pressure (PFP) and determining reassessment intervals per 49 CFR §192.712, §192.933, and §192.714. In 2024, SI convened a joint industry project (JIP) with seven participating operators, upgrading APTITUDE to a web-based platform with enhanced capabilities and accessibility that is available as of March 2025. Later this year, additional features will be introduced, providing further benefits to operators.

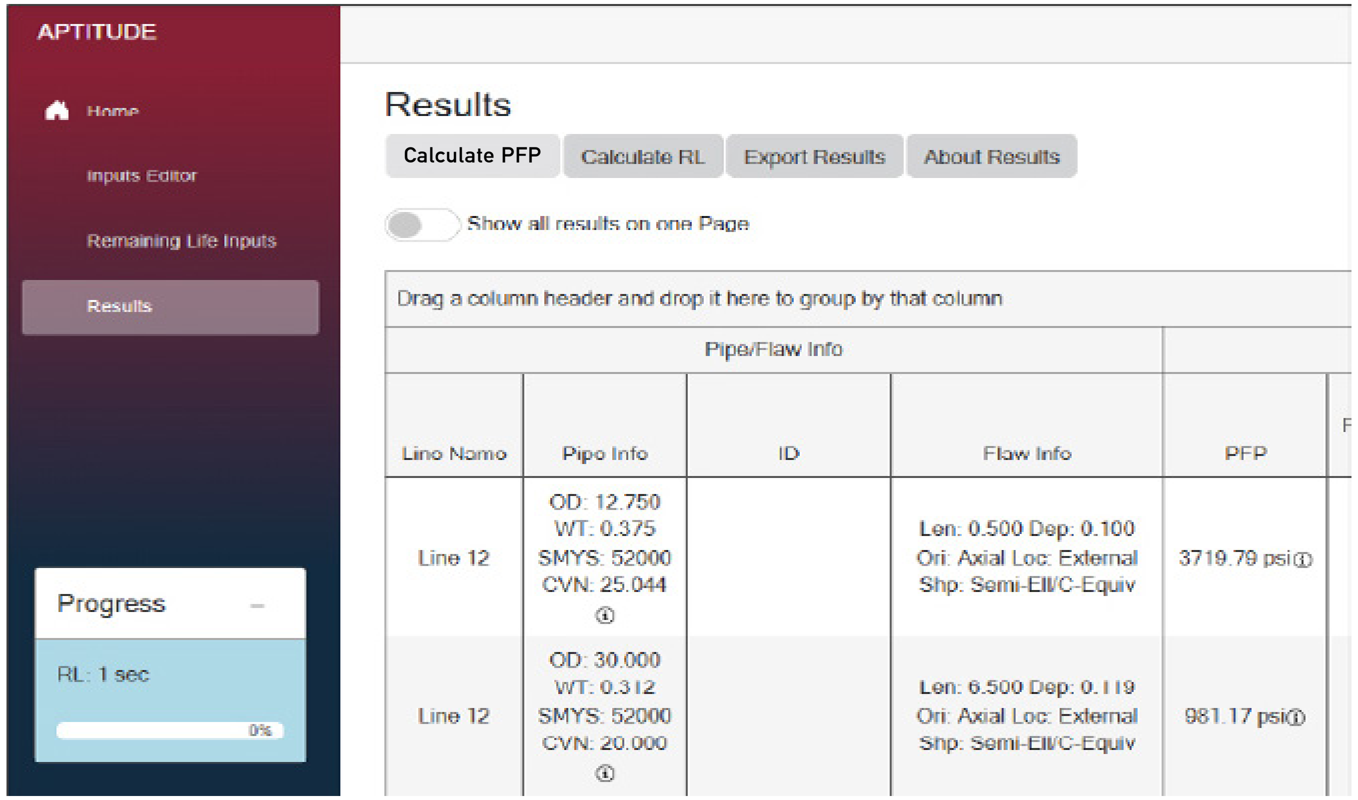


FIGURE 1. Predicted Failure Pressure and Remaining Life Calculation

The integrity of North America's pipeline infrastructure has been a growing concern, especially following significant incidents that have occurred over the last 15 years. In response, the Pipeline and Hazardous Materials Safety Administration (PHMSA) introduced comprehensive regulations under the Gas Mega Rule, specifically RIN-1 and RIN-2, to enhance pipeline safety and integrity management. These regulations mandate that operators implement rigorous inspection protocols and improved procedures to prevent future incidents. Consequently, operators are now tasked with collecting and managing extensive inspection data, necessitating the adoption of standardized software tools to efficiently analyze findings, prioritize repairs, and ensure compliance with evolving safety standards.

Recognizing this need, SI began developing and using the APTITUDE platform to calculate the Predicted Failure Pressure (PFP) for cracks and crack-like defects identified during pipeline inspections, in accordance with 49 CFR §192.712. APTITUDE also has the capability to evaluate re-assessment intervals and response criteria per the requirements of this section of code as well as §192.933 and §192.714. APTITUDE streamlines the serviceability process through a simplified interface that provides vast capabilities without unnecessary complexity, making it accessible even for users who aren't subject matter experts.

APTITUDE was originally developed in 2016 as an MS-Excel based tool, which was utilized by pipeline operators to evaluate crack and crack-like defects. A list of APTITUDE features is summarized at the top of the next page. In the years since the original development, SI has observed varying levels of understanding and efficacy in implementing PFP evaluations. In response, SI proposed a 2024 joint industry project (JIP) to upgrade APTITUDE to a cloud-based, web-enabled calculation engine, and to provide a series of training and knowledge-sharing workshops. By standardizing a web-based engine, our teams are able to eliminate installation hassles, ensure seamless updates of new features, and better support collaboration of facilities between Field Examiners and Engineers. All these aspects contribute to a streamlined evaluation of inspection data. A total of seven operators supported the initial JIP release.

Software development and basic web integration was completed in Fall 2024, after which our teams worked diligently to debug and process test for the official release. In addition, a total of three flaw evaluation workshops were hosted in 2024 to provide technical training and facilitate knowledge sharing. The meetings were well attended, reflecting a range of operator size and experience that contributed to good discussions and the establishment of best practices.

Workshop 1.
Hard spot analysis and long seam weld anomalies

Workshop 2.
Girth weld anomalies and ILI crack detection

Workshop 3.
Toughness testing and cyclic fatigue

APTITUDE was released to participating JIP operators in March 2025. Later this year, SI will implement additional features into APTITUDE, including probabilistic analysis of select features, hydrogen-assisted fatigue, and rainflow cycle counting. Through these updates and SI's ongoing support, subscribed JIP operators will have access to an efficient, cost-effective analytical tool to demonstrate compliance with pipeline safety regulatory requirements.

APTITUDE FEATURES

- Addresses a wide range of material properties, pipe and flaw dimensions
  - Yield strength, flow stress, fracture toughness
  - Diameter, wall thickness, through-wall or surface crack, crack length, depth, and orientation
- Employs various approved methodologies to calculate the most applicable predicted failure pressure
- Determines crack categories
- Calculates re-assessment intervals
- Provides Charpy V-Notch (CVN) to fracture toughness correlations
- Approximates a flow stress using different methodologies
- Incorporates measured material properties when available
- Recommends the optimal calculation methodology accounting for limitations and varying boundary conditions

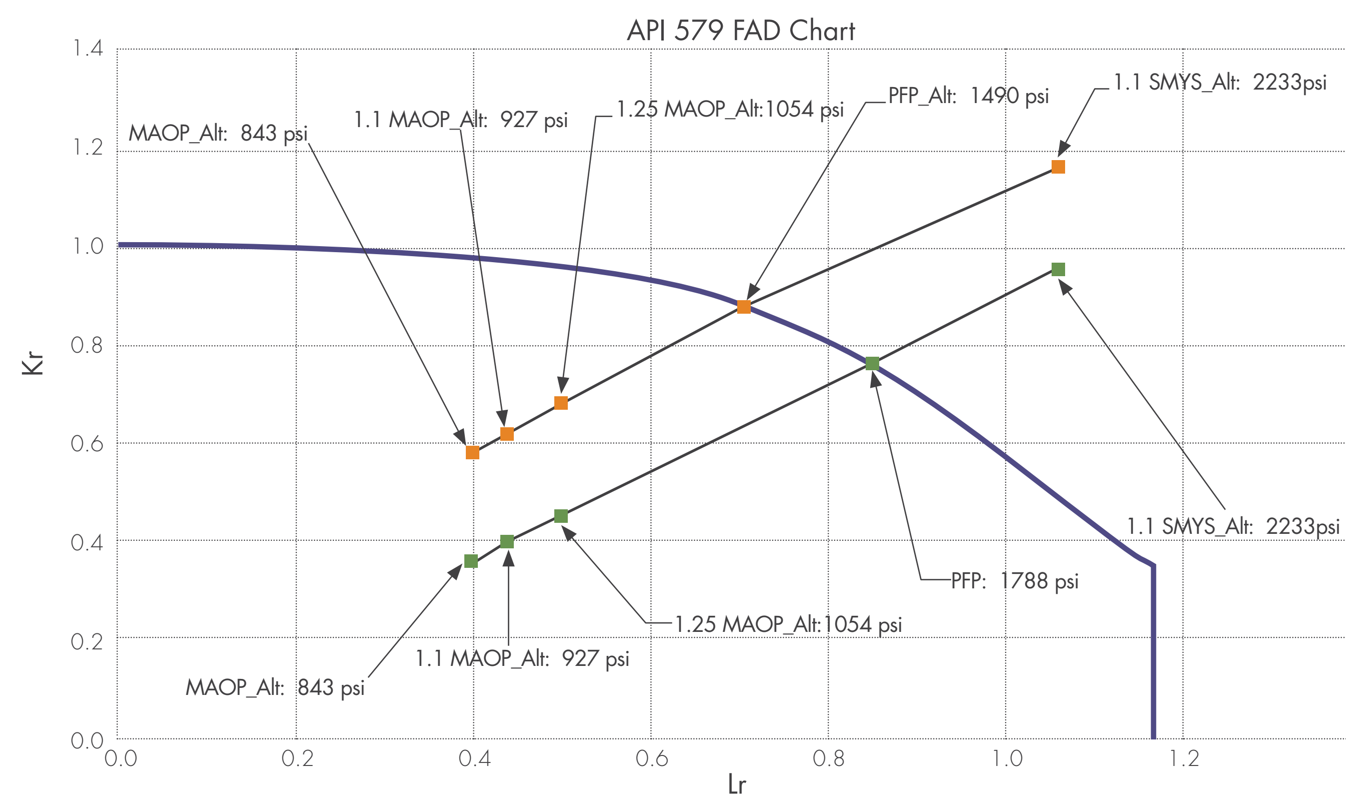
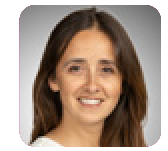


FIGURE 2. API 579 FAD Analysis with Residual

Delivering Just-in-Time Winterization Upgrades to Meet ERCOT Requirements



ELISA YATES
elisa.yates@c2cts.com

MATT McKINNEY
matthew.mckinney@c2cts.com

This article details a significant winterization effort conducted by C2C Technical Services, an SI Solutions company, on behalf of a large petrochemical facility in Texas. The project, driven by ERCOT requirements imposed in the wake of a significant 2021 storm, involved a gap analysis to identify critical instruments, detailed engineering to select appropriate mitigation measures, and just-in-time field implementation on an accelerated timetable. These measures proved effective when the facility operated without any issues during a similar storm in January 2025.

C2C TECHNICAL SERVICES

C2C Technical Services provides Instrumental and Electrical (I&E) engineering and construction support for various critical industries, including the petrochemical and power generation sectors. C2C delivers solutions with a clear focus on personnel safety and technical excellence, while providing a responsive, high-quality solution that meets the demanding schedules and expectations of their clients.

PROJECT TIMELINE

ERCOT Requirements Published
(February, 2023)

Requirements Review and Gap Assessment
(April-June, 2023)

Engineering Design & Specifications
(July-September, 2023)

Installation & Commissioning
(October-December, 2023)

In February 2021, an unprecedented winter storm brought Texas to a standstill, crippling the Electric Reliability Council of Texas (ERCOT) grid and exposing vulnerabilities across critical infrastructure. The event resulted in widespread power outages, frozen pipelines, and severe disruptions to industrial operations, forcing the energy sector to reevaluate its preparedness for extreme winter weather.

In response, leaders in critical industries (power, petrochemical, and others) took decisive action to align on a set of robust winterization requirements, and engineer then implement those solutions by the end of 2023. These measures included instrumentation and electrical (I&E) upgrades, freeze protection strategies, and system hardening measures. Applicable strategies included:

- Upgraded weather proof systems: heat tracing and enclosures ensure that vital piping and instrumentation remain above freezing temperatures.
- Improved installations: Upgrading technology and reducing deadlegs in impulse lines reduce areas that require protection.
- Enhanced Monitoring & Remote Sensing: Allowing real-time detection of temperature fluctuations and proactive intervention.

C2C was asked to support winterization efforts for a large petrochemical refining facility with an integral cogeneration plant. The project involved a gap analysis to identify critical instruments, detailed engineering to select appropriate mitigation measures, and just-in-time field implementation on an accelerated timetable.

REQUIREMENTS REVIEW AND GAP ASSESSMENT

During this phase of the project, C2C worked with site operations and reliability engineering to create criteria to determine which equipment was critical to the operation of the facility. C2C reviewed standards and historical data from the facility operator, industry best practices, and ERCOT requirements to formulate a suitable mitigation plan. With criteria established, a comprehensive review of identified plant instrumentation was conducted, identifying more than 400 instruments that required freeze hardening. Notable observations from this effort included:

- In many cases, the operator's standards went above/beyond the ERCOT requirements; C2C was able to optimize the instruments selected for hardening to eliminate unnecessary modifications.
- In other cases, lessons learned from the 2021 freeze event led to the inclusion of instruments that otherwise may have been overlooked.

ENGINEERING DESIGN AND SPECIFICATIONS

During this phase of the project, C2C's engineering team generated construction packages to support installation of the selected hardening solutions. Given the 400+ instruments in question, this was a significant logistical effort, which involved specifying materials, assisting with procurement requirements, creating drawings, and documenting installation and calibration instructions. Noteworthy aspects of this support included:

- In some cases, custom fabrication was required for enclosures and heat tracing equipment to ensure fitment and intended function. C2C worked directly with the manufacturer to implement key considerations in procurement documents.
- The project scope included replacement of numerous transmitters. C2C specified "smart" instrumentation, which imparts a digital signature on top of the 4-20 mA primary signal. As a result, critical transmitters are now outfitted with localized temperature indication, informing operators about potential freeze concerns on a customized dashboard (Figure 1) without requiring any additional instrumentation wiring.

SHGP WINTERIZATION

AMBIENT TEMPERATURE 70 DEG F | WIND SPEED 10 MPH | WIND DIRECTION SW | Winterization 2

801 TRAIN

Asset	Description	Sec. Var.	Heat Tracing Status
1FT0506A	U1 BFW PUMP A FLOW	69 DEG F	HTFP-CKT-25 OFF
1FT0506B	U1 BFW PUMP B FLOW	69 DEG F	HTFP-CKT-25 OFF
1FT0510	U1 BFW TO SH ATTEMP FLOW	69 DEG F	HTFP-CKT-25 OFF
1FT0512	U1 BFW TO HP ECONOMIZER FLOW	69 DEG F	HTFP-CKT-25 OFF
1LT5001A	U1 HRSG HP DRUM LEVEL	70 DEG F	HTP-CKT-04 OFF
1LT5001B	U1 HRSG HP DRUM LEVEL	69 DEG F	HTP-CKT-03 OFF
1LT5001C	U1 HRSG HP DRUM LEVEL	69 DEG F	HTP-CKT-02 OFF
1LT5025A	U1 HRSG LP STORAGE TANK LEVEL	69 DEG F	HTP-CKT-05 OFF
1LT5025B	U1 HRSG LP STORAGE TANK LEVEL	68 DEG F	HTP-CKT-06 OFF
1LT5025C	U1 HRSG LP STORAGE TANK LEVEL	69 DEG F	HTP-CKT-01 OFF
1PT0508A	U1 BFW TO HRSG ECONOMIZER PRES	70 DEG F	HTFP-CKT-25 OFF
1PT0508B	U1 BFW TO HRSG ECONOMIZER PRES	69 DEG F	HTFP-CKT-25 OFF
1PT0508C	U1 BFW TO HRSG ECONOMIZER PRES	70 DEG F	HTFP-CKT-25 OFF
1PT5001A	U1 HP STEAM DRUM PRESSURE	71 DEG F	HTP-CKT-10 OFF
1PT5001B	U1 HP STEAM DRUM PRESSURE	70 DEG F	HTP-CKT-10 OFF
1PT5001C	U1 HP STEAM DRUM PRESSURE	70 DEG F	HTP-CKT-10 OFF
1PT5010A	U1 HRSG HP STEAM OUTLET PRESS	68 DEG F	HTFP-CKT-19 OFF
1PT5010B	U1 HRSG HP STEAM OUTLET PRESS	68 DEG F	HTFP-CKT-19 OFF
1PT5010C	U1 HRSG HP STEAM OUTLET PRESS	68 DEG F	HTFP-CKT-19 OFF
1PT5025	U1 HRSG LP STORAGE TANK PRESS	68 DEG F	HTFP-CKT-14 OFF
1PT5028	U1 HRSG DEAERATOR PRESSURE	68 DEG F	HTFP-CKT-14 OFF

FIGURE 1. Subset of Cogen Plant Winterization Dashboard with Smart Instrument Readouts

INSTALLATION AND COMMISSIONING

C2C technicians completed field construction of the I&E upgrades either while online or using scheduled strategic outages. Commissioning was completed before the ERCOT-imposed year-end deadline. Key accomplishments during this effort included:

- Tight coordination with the operator's scheduling department to support just-in-time construction activities while online. Technicians took advantage of planned maintenance and/or equipment issues to complete installation without added downtime.
- Integration of C2C engineering and construction resources enabled rapid response to field issues (e.g., variable equipment receipt schedules, in-situ changes to construction packages, etc.).

FIGURE 3. Winterization Packages for Pressure Indicators

FIGURE 2. Winterization Package for Drum Level Transmitter

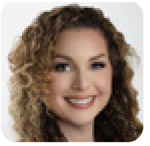
CONCLUSION

C2C Technical Services responded quickly to their clients' need for a regulatory-driven winterization project and delivered a successful solution on an accelerated timetable. C2C's in-house expertise and responsive workforce streamlined efforts and avoided unplanned downtime while completing this first-of-a-kind scope. In January 2025, the updates were tested when another significant storm impacted southern Texas. The facility was well prepared, armed with freeze-hardened equipment and real-time data, and remained fully operational during the storm.

VOLUME 55 | **NEWS AND VIEWS**

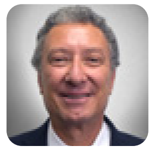
Nuclear Plant Resin Optimization

WAYNE GIBSON
mgibson@structint.com



ERICA LIBRA-SHARKEY
elibra-sharkey@structint.com

WARNER WEBER
wweber@structint.com



AL JARVIS
ajarvis@structint.com

In a nuclear power plant, the quality of water used in the primary and secondary processes is critical for safe and efficient operation. Resin selection plays a key role in maintaining water quality by removing ionic impurities and radioactive contaminants from cooling and wastewater systems to support corrosion control and minimize radiation fields while balancing O&M costs. Over time, resins become exhausted and must be replaced or regenerated, leading to waste generation, added costs, and potential operational inefficiencies. SI's Operational Support Services (OSS) team specializes in **resin optimization** programs designed to maximize resin lifespan, improve water chemistry and filtration performance, as well as reduce waste. This article details SI's industry-leading approach to resin optimization, with several case studies illustrating the measurable impact of these projects.

BACKGROUND ON RESIN USAGE

Resin typically consists of polymer beads that exchange undesirable ions with more desirable ones, helping to prevent or minimize corrosion and minimize radiation exposure. However, these benefits come at a cost, as both the initial purchase and subsequent disposal of resin is a significant O&M expense. Spent resin is typically classified by radioactivity levels, Class A, Class B, or Class C, and disposal costs range greatly. In addition to cost savings realized from optimizing resin configurations and purchasing, annualized disposal cost savings from reduced radioactive waste disposal support a thorough evaluation of resin programs at nuclear power plants.

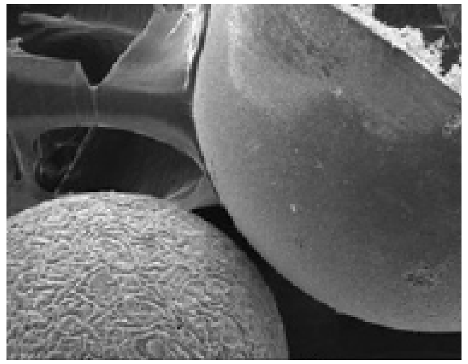


FIGURE 1. Scanning Electron Microscope images of cation and anion resin beads

While the fundamental purpose of resin is the same across nuclear plants, its application differs between pressurized water reactors (PWRs) and boiling water reactors (BWRs):

	PWRs (PRESSURIZED WATER REACTORS)	BWRs (BOILING WATER REACTORS)
Applicable Systems	On the primary side, resin is used in the chemical and volume control system (CVCS) and spent fuel pool (SFP) system to maintain water purity, remove contaminants, and control pH and reactivity. On the secondary side, resin is used in steam generator blowdown, condensate polishing, and moisture separator drains.	Resin is used in the Radwaste, Condensate Polishing (CDP), makeup water and Reactor Water Cleanup Systems (RWCU) to maintain water clarity and minimize impurities before water is returned ultimately to the reactor.
Use Cases	■ Online purification beds (mixed bed, in-service during power operations) ■ Cation (delithiation) beds – used to periodically remove lithium from the reactor coolant system (RCS) ■ Anion (deboration) beds – used to remove boron from RCS at end of cycle ■ Outage purification beds (mixed bed, in-service during outages) ■ Steam Generator Blowdown Demineralizers ■ Condensate Polishing Filter/Demineralizers and Deep Bed Demineralizers ■ Moisture Separator Drain Filter/Demineralizers and Deep Bed Demineralizers (used at Once-Through Steam Generator units)	■ Deep Bed Demineralizers (mixed beds, operate for ~3-4years) ■ Condensate Filter Demineralizers (F/Ds) (powdered resin, operate for ~20-40 days before the F/Ds are backwashed and precoated with new resin) ■ RWCU deep bed demineralizers (mixed beds)
Key Resin Functions	■ Removing chloride, sulfate, and corrosion products ■ Managing lithium and boron levels for reactivity and pH control ■ Reducing radioactive contaminants in spent fuel pools	■ Filtering impurities from the steam cycle (ionic and radioactive) ■ Preventing contamination from condenser leaks ■ Extending the life of deep-bed resins by optimizing anion/cation ratios
Typical Usage (per cycle):	■ For radioactive primary systems, 100 to 230 cubic feet, depending on plant design	■ Condensate Deep Bed Plants (680 to 1920) cubic feet ■ CF/D Plants (1290 to 2900) cubic feet
Other Considerations	■ High condensate temperatures (>120°F) can degrade resin performance over time	

RESIN OPTIMIZATION APPROACH

Resin optimization is a data-driven process that balances cost savings, chemistry control, and operational reliability. Many nuclear sites use more resin than necessary, leading to higher procurement and disposal costs without additional benefit. Our team works closely with sites to analyze resin performance, historical loading trends, and chemistry requirements to determine whether adjustments can be made without adversely impacting plant operations.

Key steps in the optimization process include:

- **Assessing Current Resin Usage**: Reviewing baseline chemistry and operational conditions to identify potential inefficiencies.
- **Evaluating Licensing and Regulatory Considerations**: Ensuring that any reductions in resin usage comply with site licensing requirements (e.g., UFSAR assumptions on failed fuel scenarios).
- **Adjusting Resin Loading**: Identifying opportunities to reduce resin volume while maintaining or improving performance.
- **Optimizing Resin Composition**: Adjusting cation-to-anion resin ratios or resin type to better match site-specific chemistry.
- **Mitigating High-Temperature Degradation**: Recommending resin formulations that can better withstand elevated condensate temperatures, which has become increasingly relevant for a number of nuclear sites.
- **Implementation Planning**: Developing a phased approach to gradually introduce changes, ensuring seamless integration into site operations.

EXAMPLE #1: DETAILED FLEET RESIN ASSESSMENT

The SI team conducted a comprehensive resin optimization analysis for a nuclear utility fleet, which consists of both PWR and BWR reactor types. For each site, the current resin strategy was reviewed for opportunities to reduce purchase and disposal costs while maintaining performance and regulatory compliance (UFSAR requirements). Key findings from the study are summarized as follows:

- At one of the PWR locations, there was no opportunity to reduce resin volume, but the team identified an opportunity to implement more cost-effective resins already in use elsewhere in the fleet. In addition, optimized cation to anion resin ratios were recommended to improve bed longevity. These actions resulted in annual savings of more than $60,000.
- At a BWR location, the team confirmed that the existing resin strategy is effective. An alternative resin was recommended to improve chemistry performance, though it did not offer direct cost savings. However, several potential equipment upgrades were identified which would have measurable cost savings if implemented.
- At a separate PWR location, the team identified an opportunity for resin volume reductions (20 cubic feet per fuel cycle) in addition to other optimizations. This led to significant savings in both purchase and disposal costs, totaling almost $160,000 per year.

Overall, the resin optimization project for the nuclear utility fleet was very successful, identifying potential performance enhancements and netting the utility **more than $220,000 in annual savings**.

EXAMPLE #2: FLEET-WIDE OPTIMIZATION STUDY

SI performed a similar study for a different nuclear utility fleet with a mix of BWR and PWR units. The study was highly quantitative, analyzing existing operational chemistry behavior of the historical resin programs being implemented at each site. Through this process, the team identified numerous opportunities to reduce resin usage while maintaining or improving performance. The study also provided an opportunity to benchmark the sites against best practices within the fleet and the industry at-large and identified instances where standardizing resin strategies (as appropriate) would result in improved operational performance at certain individual sites. **In total, SI's recommendations have the potential to save the fleet over $1M in operating costs annually**. SI's OSS team is actively supporting implementation of these recommendations at several additional sites.

CONCLUSION

Resin optimization is a proven strategy for nuclear plants seeking to improve chemistry control while reducing operational costs and radioactive waste. By taking a quantitative approach, SI has helped major utilities identify measurable improvements in resin usage, achieving **millions of dollars in annual savings**. With increasing industry focus on efficiency and waste reduction, proactive resin management will continue to be a key driver of operational excellence.

This structured approach has helped multiple nuclear fleets reduce resin procurement and disposal costs by hundreds of thousands to millions of dollars per cycle, while maintaining chemistry control and reactor efficiency.

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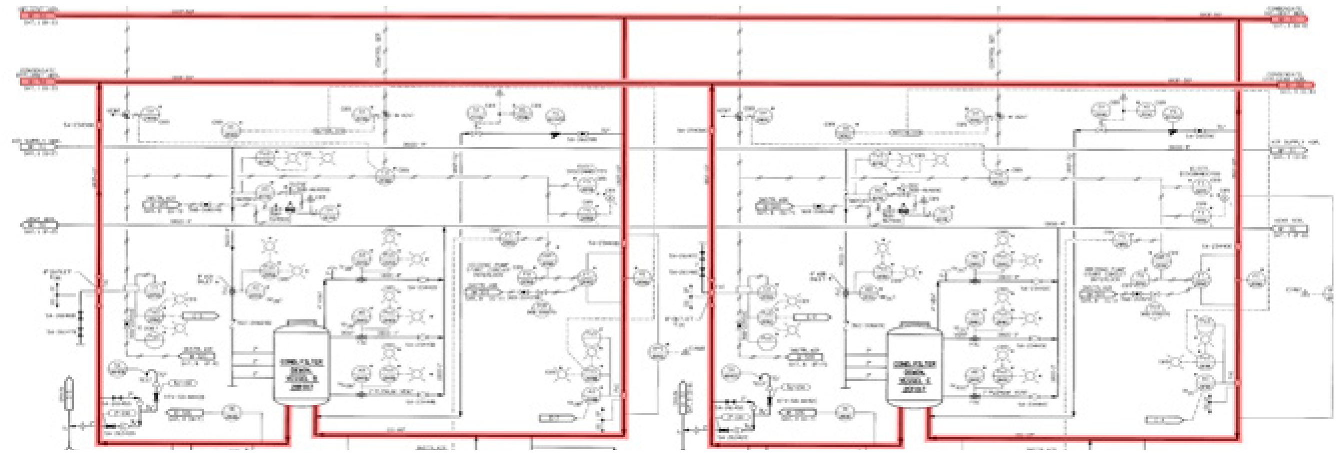
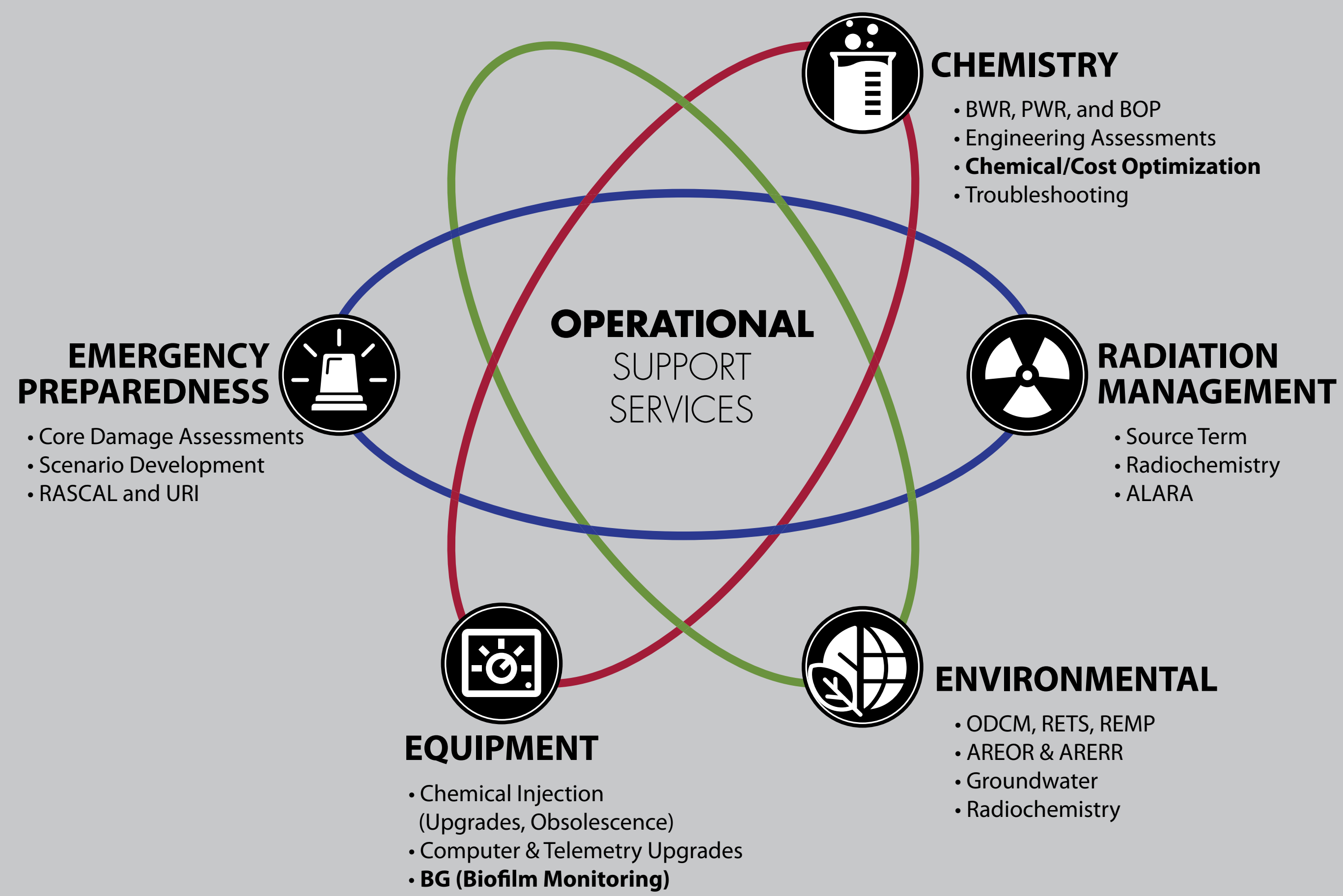


FIGURE 2. Layout of Condensate Filter/Demineralizer Beds at a BWR Plant

SIA has been servicing the nuclear power industry with specialized chemistry solutions throughout our decades of experience and operation. As we continue to grow and evolve, our Operational Support Services (OSS) group has expanded our service offerings into several new areas including, Radiation Management, Emergency Preparedness, and Environmental, while simultaneously advancing our Chemistry and Equipment support. Our experienced staff look forward to continuous advancements in nuclear and non-nuclear spaces to support our clients in all their needs.



Digital Twins - Concept, Uses, and Adoption in Industry

SARBAJIT GHOSAL
ghosal@scsolutions.com

DICK de ROOVER
dderoover@scsolutions.com

ABBAS EMAMI-NAEINI
emami@scsolutions.com

Digital Twins are dynamically synchronized digital representations of physical equipment or systems. This technology is emerging in the power generation industry and assists with early detection of potential failures, failure accommodation, optimized maintenance schedules, development of next-generation equipment, and workforce training.

SC SOLUTIONS

SC Solutions has decades of experience with technology that powers devices in your pocket and on your desk and continues to be an industry leader in providing process control solutions to the semiconductor industry. SI Solutions brings together the combination of SC's controls expertise with that of Structural Integrity's, modeling expertise and highly capable AIMS platform cyberinfrastructure, cultivating the total package to handle the development of digital twins in critical infrastructure.

ORIGIN OF THE DIGITAL TWIN CONCEPT

On April 13, 1970, while 210,000 miles from Earth, the three astronauts in Apollo 13 were startled by a loud bang that shook their tiny spacecraft. Astronaut John Swigert immediately messaged the NASA Mission Control Center: "Houston, we've had a problem here." One of the two oxygen tanks had exploded catastrophically, damaging the other tank and thus putting the astronauts in extreme danger. The mission had to be aborted.

NASA engineers and scientists in Houston worked feverishly around the clock to devise a way to bring the astronauts back safely. They were assisted by 15 simulators used to train astronauts and mission controllers in every aspect of the mission, including multiple failure scenarios [1]. These simulators, made up of high-fidelity models, had been developed at NASA in the 1960s as "living models" of the mission [2]. They were controlled by several networked computers, e.g., four computers for the command module simulator and three for the lunar module simulator [1]. By utilizing these simulators and real-time sensor data from the spacecraft, Mission Control devised a successful strategy to guide the astronauts back to Earth safely.

While the term "digital twin" was coined later, the Apollo 13 mission is widely recognized as the first application of this technology, where a digital version of a physical system was updated with sensor data which was then used to run simulations to test potential solutions to troubleshoot a complex, high-stakes problem in real-time.

WHAT EXACTLY IS A DIGITAL TWIN?

Claims of using digital twins to solve various problems and marketing supposed digital twin products have proliferated over the past seven years. The term's use to describe virtual representations of all sorts of assets, ranging from cities to racing cars, has led to considerable confusion. Experts from academia, industry, government agencies, and standards organizations have published definitions describing the key features of digital twins to mitigate confusion [3]-[5].

Since the definition often gets bogged down in semantics, it is preferable to identify the three primary parts that constitute a digital twin (DT). They are the physical object or process and its physical environment, the digital representation of this object or process, and the communication channel between these two that helps maintain state concurrence of the digital representation even as the state of the object or process changes dynamically. This communication channel transmits sensor data and state information and is called the digital thread. It is noted that a static model of a system or process cannot be a DT. A dynamic model whose parameters are not updated to reflect changes in the physical counterpart of the model also cannot be a DT.

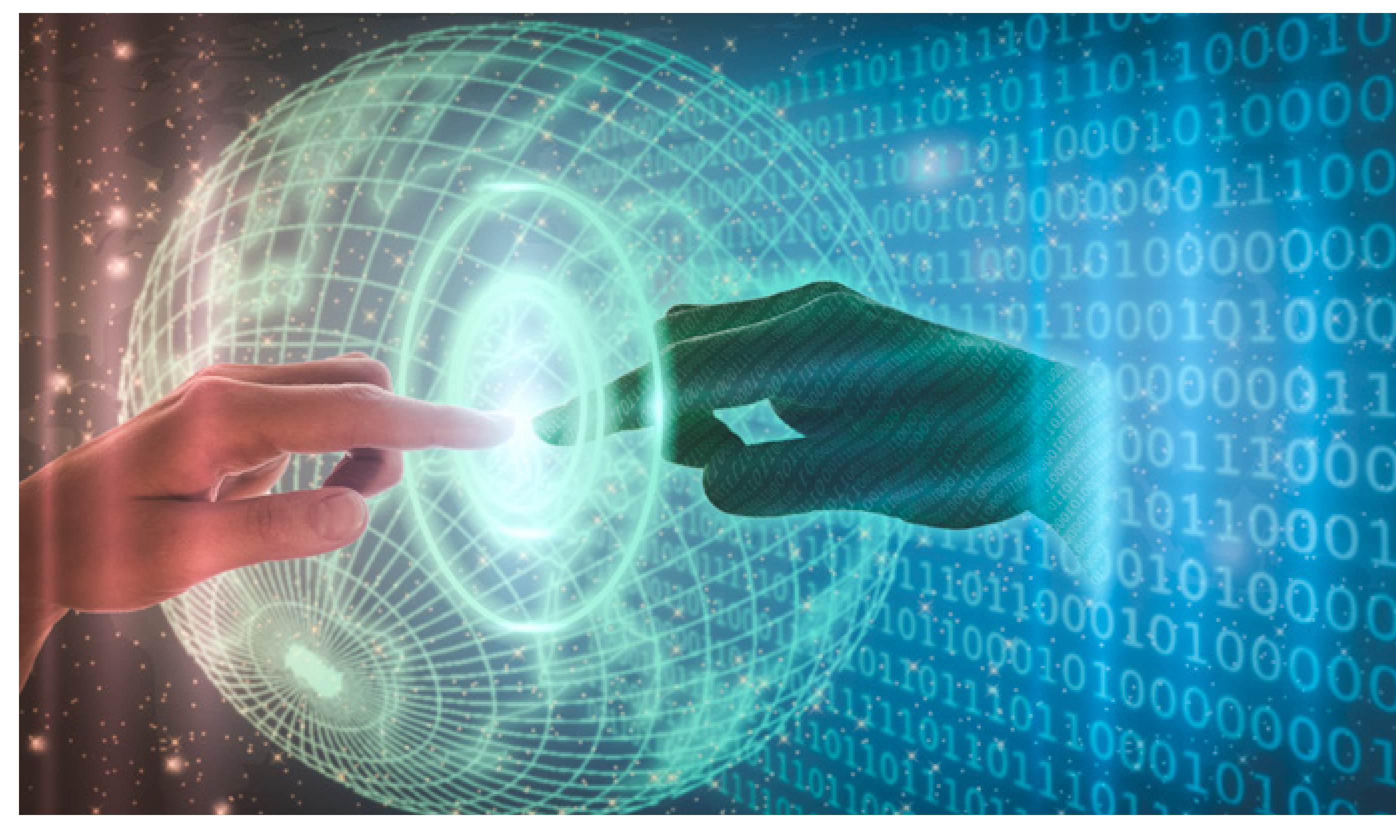
The International Organization for Standardization (ISO) adopted a concise yet complete definition of a digital twin in 2021. The standards document on the digital twin framework for manufacturing (ISO 23247 [5]) defines a digital twin as a "fit-for-purpose digital representation of an observable manufacturing element with synchronization between the element and its digital representation" [6].

Whether maximizing machine performance or preventive maintenance, a clear goal for the twin is necessary for selecting the states of interest and a corresponding model of sufficient fidelity.

A digital twin of the next-generation machine, a digital twin prototype (DTP), incorporates its physical twin's design specifications and engineering requirements. The DTP is valid in the design phase before investing resources to build a hardware prototype. DTP simulations help designers decide whether the eventual prototype would meet performance specifications.

Once the prototype is fabricated and operational, the corresponding DT, now updated with sensor data, is called the digital twin instance (DTI). A collection of DTIs with a standard function is called a digital twin aggregate (DTA). DTA's may be a collection of digital twins of the same equipment, e.g., several nominally identical pumps in a hydroelectric power station, or different equipment with a common purpose, e.g., robots, conveyors, and quality inspection stations in a material handling system of a factory.

Additionally, a simulation with a DT does not necessarily have to be performed in real-time—it would depend on the application. A DT used



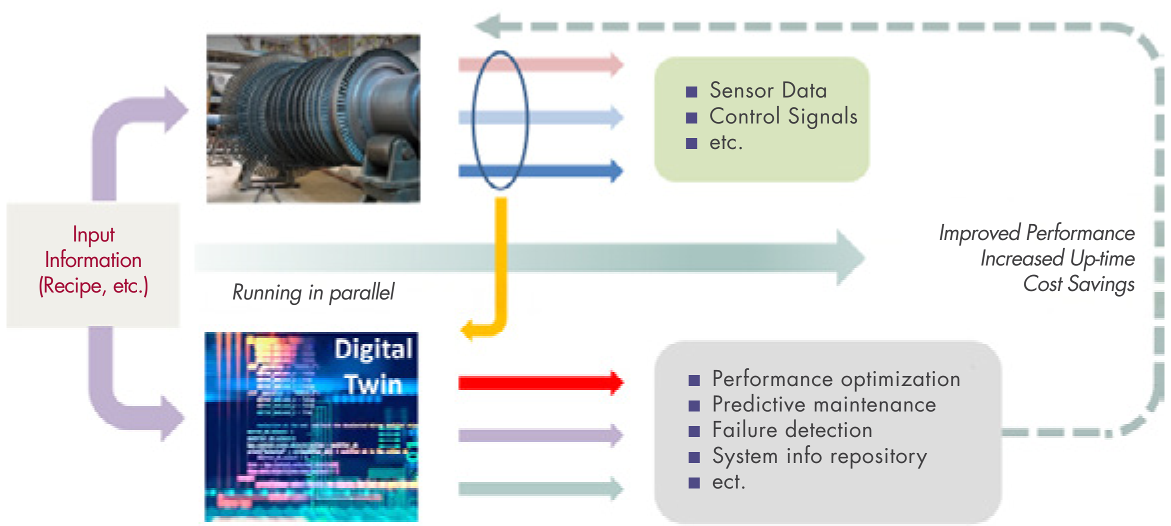


FIGURE 1. Digital twin (DT) of a power generation equipment operating in parallel with its physical twin.

for real-time system control must run faster than real time. However, a high-fidelity DT used for design optimization may run simulations over many hours to sufficiently probe the parameter space in its underlying models.

DTs have three key aspects: model, data, and services, i.e., services used or provided by DTs. The software that makes up the DT of a system has different functionalities that address these three aspects. We have divided the software into six broad classes:

SIX CLASSES OF SOFTWARE USED IN A DIGITAL TWIN SYSTEM

Software implementation of models: These may be physics-based models or gray box models (a combination of physical subsystem models and input-output heuristic models) of the physical components that may be integrated to create the system DT. The physics-based models are low-order versions of complex finite-element models that run simulations faster than in real-time. The gray box models combine known physical/mathematical relationships (the system model – the "white box" part) with phenomenological relationships or black-box models such as artificial intelligence/machine learning (AI/ML) that replace physics too complex to be modeled or overlooked. One example of gray box models is surrogate models such as Gaussian process models and physics-informed machine learning (PIML).

Sensor data-related software: This group includes software for signal processing and noise filtering of the sensor data. The data acquisition frequency may vary from milliseconds for real-time sensor data to hours for statistically sampled measurements of attributes of a manufactured product. Depending on the number of sensors and sampling rate, the volume of data may be substantial, especially in a manufacturing application. There is also software for interacting with external databases that would organize and store the data, make them available for updating the DT, and help perform prognostic tasks. This class of software would also include the implementation of sensor fusion algorithms and data compression algorithms.

Analytical and prognostic software: This class of software provides the DT's "intelligence" and its benefits to the user. It includes the implementation of predictive maintenance algorithms, system performance optimization, decision support, and anomaly detection. Also included is software for updating models with sensor data by estimating new model parameters or re-training machine learning networks.

Software that enables user interaction: A well-designed user interface is key to digital twins gaining wider acceptance. A DT should include tools for customizing dashboards and interactive control interfaces, 3D graphics libraries for visualization of the physical twin at different levels of detail, and reporting tools for its prognostic and related functions. Some DTs may benefit from using augmented reality/virtual reality (AR/VR) tools.

Network communication and security software: This software is part of the so-called "digital thread" that involves all aspects of securely dealing with data streaming from hundreds, if not thousands, of sensors. Tasks performed by such software would include message queuing, protocol translation, connection monitoring, API management, and, very importantly, network security. For DTs to gain trust, the intellectual property (IP) embedded in the DT and in the data must be protected against all cyber threats.

Administrative software: This group includes "everything else"! It provides software and tools for configuration and change management, requirements tracking, documentation, access control, resource monitoring, and backup.

DRIVERS FOR DIGITAL TWIN DEVELOPMENT

The confluence of advances in four technological factors has driven the development and adoption of digital twin technology over the past decade. These factors are:

1. The decreasing cost of high-performance computing (HPC), both at the edge (i.e., in physical proximity to the end-user or the physical twin) and in the cloud. While problematic limitations imposed by physics and manufacturing costs have slowed Moore's Law, computational power has continued to increase through a combination of heterogeneous integrated circuit (IC) architecture, such as 3D stacking and chiplets, and chips designed for a specific use, such as graphics processing units (GPUs).

2. The proliferation of sensors and sensor networks (sometimes called the Internet of Things or IoT) enables individual sensors to acquire, flow and store data. Data analysis makes it possible to monitor a variety of system attributes, which, in turn, allows the digital twin to keep up with changes occurring in its physical twin.

3. Availability of software tools enabling faster development of more complex models. Modeling techniques have been developed to use different models, including physics-based, data-driven, and machine learning (ML) models, to create a more comprehensive and accurate digital representation of the physical system. Merging various modeling approaches helps capture a more precise view of the physical system by leveraging the strengths of each model type. Commercial modeling software such as ANSYS also provides tools to develop surrogate models, proxies for high-fidelity physics-based models, and speed up model simulations [7].

4. The arrival of large language models (LLMs) developed in the field of generative artificial intelligence. Before the release of ChatGPT to the public in November 2022, the role of AI in digital twins was primarily in using supervised machine learning for surrogate and data-based models. LLMs have advanced "embedding" capabilities, i.e., they can significantly compress data (both numeric and text) while retaining essential information. For example, in a manufacturing setting, LLMs can organize data from maintenance logs, equipment images, and operational videos and make them available in a DT. Maintenance logs often have valuable information related to system failure diagnostics and health maintenance that would add to the DT's capabilities. AI is expected to play an essential role in the future of digital twin technology.

The fast-paced progress made in the above technologies makes it possible to transform digital twins of complex systems from merely a nebulous concept to a valuable technology that can be implemented once a few hurdles (such as standardization and data sharing) are overcome. Figure 2 attempts to show how the digital twin concept has evolved from solid models and offline computations to the virtual representations of complex systems being developed.

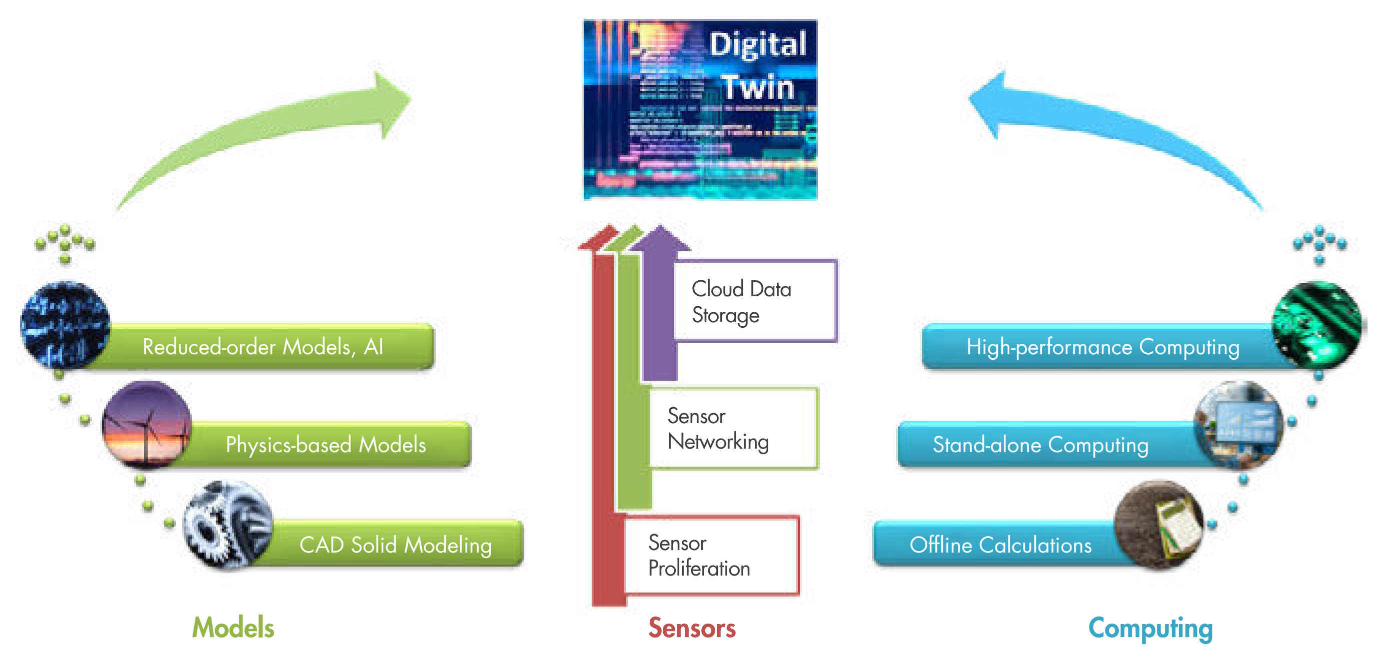


FIGURE 2. Factors in the evolution of digital twins.

HOW CAN DIGITAL TWINS BE USEFUL?

The holy grail of digital twin technology derives from its ability to monitor the health of its physical twin, and the benefits include the following:

Early detection of potential failures: While sensors in the physical twin can monitor the system's local state in the proximity of the sensors, the digital twin's states act as virtual sensors and effectively scan the state of the entire system and can detect anomalous behavior. When the DT incorporates reliable degradation models (e.g., heater degradation or crack propagation), it can predict potential failures. The process cycle may then be ended in an orderly manner to repair or replace the part without any damage to the system that may result from a catastrophic failure of the part.

Failure detection and accommodation: The digital twin can be a valuable tool in case of a component failure in equipment. There are different ways to perform such root cause analysis. One way is to use physically meaningful model parameters continually monitored by sensor data estimation. If a parameter value strays outside a specified range, the failure is related to the component associated with that parameter. A second method uses a bank of Kalman filters to detect anomalies. The second article in this series will examine failure detection for sensor and actuator failures in a rapid thermal processing (RTP) system in greater detail.

As an example of using DT for failure accommodation, if a temperature sensor fails in the RTP system, the DT's estimate of the system's temperature near the sensor (one of the DT's states) can temporarily serve as a virtual sensor. The process can continue until the faulty sensor is replaced during regular maintenance.

Optimizing maintenance schedules: Currently, scheduled maintenance of equipment is more frequent than needed to avoid unplanned downtime. The ability to foresee some potential problems down the road allows a factory to implement predictive maintenance strategies to reduce cost by eliminating unnecessary maintenance.

Develop Next-Generation Equipment: The digital twin of an existing asset may be modified to help speed up the development of next-generation equipment. Simulations run with the latter are very helpful in determining whether the design would meet the desired performance goals. Design changes are fast and inexpensive to implement and test in virtual space, and they can help ensure that the prototype built would meet all the requirements. SC has used this approach with its equipment models, which are components of the equipment DT, to help its customers design and build next-generation equipment.

Workforce Training: Since the roots of digital twins go back to NASA's simulators for training astronauts, it is not surprising that DTs are finding a role in the education and training of the industrial workforce. Here, DTs can provide an immersive learning experience and practice with virtual control of tools to run real-time simulations, often aided by virtual reality accessories. Like other digital educational tools, DTs have the advantage of offering customizable learning, distance learning, and a safe environment without any accidents resulting from incorrect operation. Finally, DTs can be used for scenario-based training dealing with various operational conditions, equipment failures, and emergency response training. While the prognostic applications of digital twins require very frequent updating with sensor data, the DTs for other applications need significantly less updating.

POTENTIAL APPLICATIONS FOR DIGITAL TWINS IN POWER GENERATION AND OTHER CRITICAL INFRASTRUCTURE

The digital twin paradigm offers promise in the energy industry where a DT is developed and maintained to identify changes in the system that helps detect anomalies, make maintenance decisions, or perform root cause analysis of failures. A finite element (FEM) model of a structure with a crack which is periodically updated with measurements of the crack dimension may be considered to be a DT of the structure whose purpose is to monitor crack propagation. One may scale up such models to larger structures, e.g., large components of energy systems such as gas turbines [8].

The application of DT technology to combined gas turbine, wind turbine, solar, and nuclear power plants are expected to increase in the years ahead with several application areas in the nuclear industry [9]. These include design, licensing, plant construction, training simulators, autonomous operation and control, failure and degradation prediction, physical protection modeling and simulation, and safety/reliability analyses [10].

SI's expertise in FEM modeling, material degradation, and lifetime prediction models, together with the AIMS development team's expertise in cyberinfrastructure, is well suited to building and maintaining a DT of an energy system or some other critical infrastructure and using the DT for preventive maintenance and other applications. DT is an evolving technology, and it may not be possible to fully automate the model updating process. Hence, the software as a service (SaaS) model may become the norm for DT products. SI is optimistic about the technical aspects of DT Technology and the opportunities to leverage these tools in supporting our clients.

VOLUME 55 | **NEWS AND VIEWS**

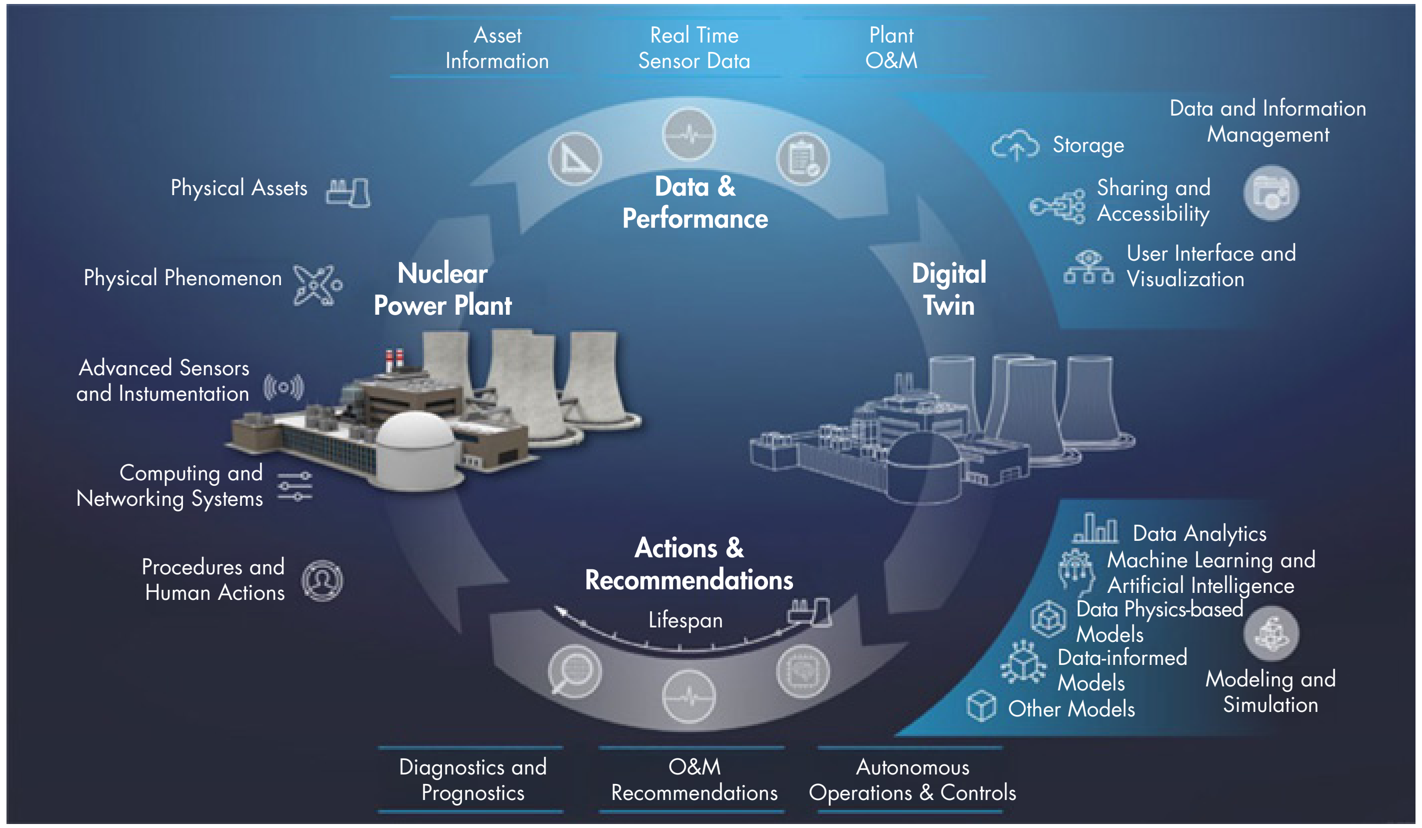


FIGURE 3. Digital twin concept for a nuclear power plant [10]

POWER GEN APPLICATIONS

With the emergence of Digital Twins in the power generation industry, our teams are able to use the synchronized digital representations of equipment to assist with early detection of potential failures, failure accommodation, optimized maintenance schedules, development of next-generation equipment, and workforce training.

Our staff are positioned to support digital twins' development, coinciding with SI's modeling expertise and highly capable AIMS platform cyberinfrastructure, cultivating the total package to handle any digital twins' needs. The AIMS Digital Solutions platform is integral to our mission of providing the best-in-value, innovative, fully integrated asset lifecycle solutions. Digital products paired with our expertise in Engineering, inspections, and analytics help achieve a holistic asset management approach to our clients.

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Pre-Planning for Investigations of Catastrophic Events

CLARK McDONALD, PhD
cmcdonald@structint.com

Facilities that plan ahead for failure investigations are more likely to quickly identify the root cause of issues and implement effective corrective actions. Structural Integrity Associates (SI) can assist with pre-planning needs, and can also assist with incident investigations and failure analyses of components of interest.

INTRODUCTION

When a catastrophic event occurs in an industrial environment, normal operations are abruptly thrown into chaos. For well-prepared facilities, the extent of chaos can be greatly controlled, or potentially eliminated. How can organizations prepare for major events of this type?

First and foremost, consideration should be given to the post-incident safety of personnel. Most facilities have well-developed evacuation plans, safety procedures, and damage mitigation procedures in place. But what happens when everything calms down? Facilities that pre-plan for the early stages of the investigation process have the best chance of learning the cause(s) of the event and are, therefore, more likely to implement appropriate changes to prevent similar events in the future.

THE CALM AFTER THE STORM

After safety procedures have been implemented, and the chance for additional injury or damage has been eliminated, the investigation process can begin. Regardless of whether the investigation process is handled by internal personnel, federal or state investigators, insurance representatives, independent consultants, or some combination of the above, the preservation of information and evidence is critical. An additional consideration is the potential for legal disputes that might stem from the event, and in some instances, investigators may be working under the direction of attorneys who are trying to protect and preserve this critical evidence.

An outline describing some of the basic steps involved in the preliminary investigation process is provided in Table 1. However, the best pre-planning program involves breaking down each of the steps into more specific tasks and goals, and targeting key plant personnel, from senior management to plant workers, for education on documentation, preservation, and the need for a step-by-step approach to moving forward after the 'storm' has passed.

WHAT IS MOST IMPORTANT IN THE LONG RUN?

Balancing the pace of a post-incident investigation is one of the most difficult goals for those involved in figuring out what happened. Industrial facilities are generally in place to make a profit for their owners, and this often triggers pressure for rapid clean-up, reconstruction, and return to operation. Under such pressure, untrained employees may strive to return to operation without considering the impact of lost information or evidence. Even when the preservation of important artifacts is attempted, employees who lack proper training or input may inadvertently lose or destroy important evidence. The desire to get the unit back into operation quickly must be balanced against the need to accurately determine the cause(s) of such an event.

The good news is that it is possible to effectively collect and preserve important information and evidence while simultaneously making great strides toward a return to normal operation. If plant personnel are properly trained, and pre-planning for the days following major events is in place, appropriate investigative and documentation procedures can be implemented more efficiently, and critical information and artifacts can be preserved for the ongoing investigation. In the long run, such preparation will allow for more accurate causal analyses and may also draw attention to critical operations and associated safety functions within the facility.

EXTERNAL SUPPORT FOR PRE-PLANNING AND INVESTIGATION

SI has experience dealing with investigating catastrophic failure events and can provide guidance or training related to preparation and pre-planning. For example, the development of site-specific recommendations and checklists may help to guide plant staff in the event that a major incident occurs. Further, high-level "awareness" training could improve plant staff readiness and increase familiarity with the site-specific plans, thereby increasing efficiency in executing appropriate actions after a major failure event.

Table 1. Outline of Basic Preliminary Investigation Procedures+

With regard to evidence preservation, SI's Material Science Center (MSC) has expertise in failure analysis and can provide guidance or input on properly handling remnant (broken) parts or other components of interest to protect critical evidence. More specifically, preventing further mechanical damage or corrosion of fracture surfaces ensures that the failure mode can be assessed in a laboratory environment. Where corrosion is present on failed parts, protecting the parts from contamination allows for subsequent analyses to identify corrosion mechanisms that may have been a factor in the failure event.

SITE PRESERVATION

- Protect incident site information – only key personnel should be allowed access to the incident area, and these personnel should be trained to avoid altering the site so that key information is maintained. Equipment and related items should not be removed, disassembled, or otherwise tampered with until the site is thoroughly documented.
- Documentation of the site – site information should be recorded using photography, videography, measurements, drawings, mapping, etc. Locations of all items of importance, large and small, should be thoroughly documented and tagged or labeled as necessary.

OPERATIONAL DATA COLLECTION

- List equipment – develop a list of all equipment, components, systems, etc., involved in the process or damage area.
- Collect operational data – operational data for each component, system, process, etc., should extend as far back in time as is practicable and should include both normal and abnormal operating conditions, if both exist.
- Collect appropriate drawings and manuals – information pertaining to equipment or system construction or operation, including drawings, maintenance documents, manuals, etc., should be located and preserved.

WITNESS FEEDBACK

- Documentation of observations by key personnel – those familiar with the equipment or systems involved in the incident should be interviewed to record information regarding normal operations and anything abnormal that occurred before the event.
- Documentation of observations by other personnel – employees who work in or near the incident area, even if not familiar with the involved equipment, should be interviewed to record their observations before and during the event.

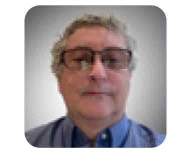
CRITICAL COMPONENT PROTECTION AND PRESERVATION

- Critical equipment and components – any equipment, tool, or component that is potentially associated with the cause of the failure event should be preserved, without alteration, in its post-accident condition.
- Fractured parts – cracked or broken items should be protected and preserved for further evaluation in a laboratory environment. Additional damage or contamination of the part, and particularly the fracture surfaces, should be avoided.
- Exemplars – if fractured parts are suspected of failure leading up to the event, any available similar parts should be preserved for evaluation along with the fractured parts.
- Manufacturer's information – information regarding the source, manufacturer, maintenance history, and related information for any suspect parts or equipment should be collected for evaluation.
- Multiple part assemblies – equipment or tools consisting of multiple components should be preserved in their entirety and should not be disassembled until the disassembly process can be thoroughly documented.

+Also refer to ASTM E1188, "Standard Practice for Collection and Preservation of Information and Physical Items by a Technical Investigator", and ASTM E860, "Standard Practice for Examining and Preparing Items that Are or May Become Involved in Criminal or Civil Litigation".

Steam Turbine Failure Cause Evaluation

JOHN MOLLOY
jmolloy@structint.com



DAVE KING
dking@structint.com

This article summarizes SI's independent root cause analysis of a catastrophic steam turbine failure at a coal-fired power plant. The investigation identified that creep-driven rotor material liberation in the intermediate pressure (IP) turbine was the initiating cause of the event, which led to severe damage throughout other portions of the turbine-generator train. SI provided metallurgical evaluation, detailed finite element analysis, review of operating data, and customized extent-of-condition inspection plans to assess fleet-wide risk and prevent subsequent failures.

THE EVENT

The SI Turbine and Generator (T&G) team performed an independent Root Cause Analysis (RCA) for a steam turbine event, which resulted in substantial damage to the intermediate pressure (IP) steam turbine (ST), the high pressure (HP) ST, unit bearings, and steam supply piping. The event also damaged the low pressure (LP) turbines and generator but to a lesser extent. The site in question consists of three conventional subcritical coal fired units that were commissioned in the late 70's and early 80's. The units are similar, featuring comparable installed equipment, a shared bearing configuration, and an output rating of 800MW each.

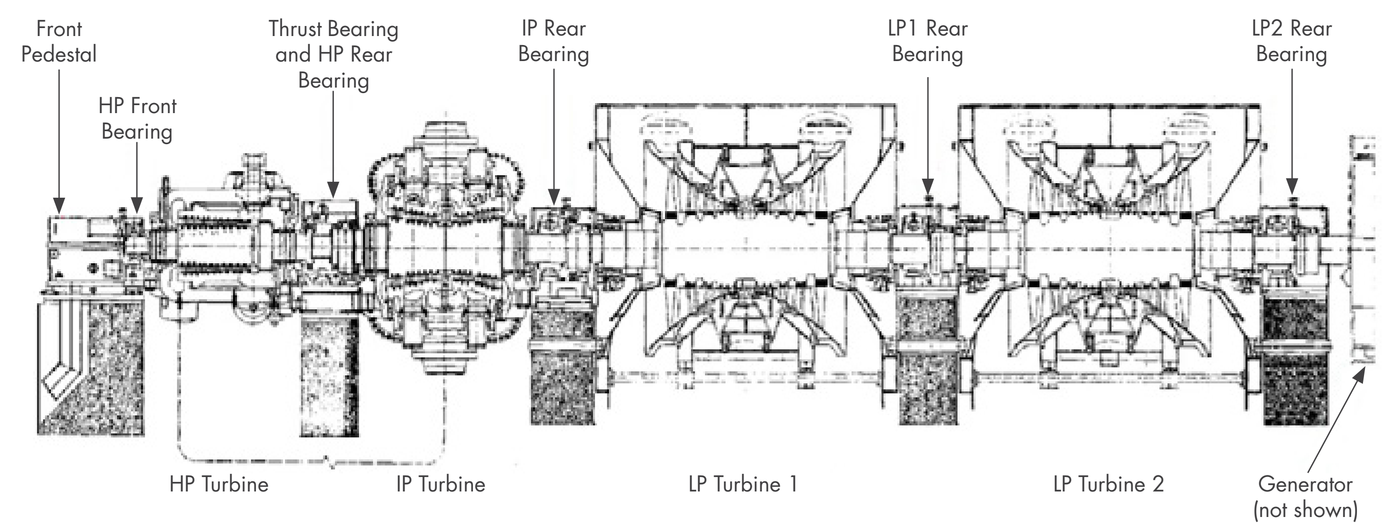


FIGURE 1. Steam Turbine Cross Section

Prior to the event, the unit had been online approximately 2 weeks before a reserve shutdown or “market outage.” During the reserve shutdown, no maintenance was performed on the STG. On the day of the event, the Independent System Operator requested the unit to be online at minimum load and capable of automatic dispatch by midday. The unit synchronized to the grid early that morning with no issues.

At the time of the incident, the unit was operating at 35% load. The operators felt a major vibration and heard a loud banging sound. Shortly thereafter, the turbine tripped offline on loss of control fluid pressure which subsequently tripped the boiler, and the generator tripped on reverse power. The event generated severe damage in and around the STG including fires within the turbine galley.

Initial investigation indicated severe damage to the HP, IP, and LP turbines (refer to rotor cross section in Figure 1). External observations of the STG indicated damage to piping and bearings along the drivetrain. The HP bearings and IP rear bearing were found heavily damaged with the bearing caps and coupling guards knocked off. The LP1 rear bearing was also identified to have coupling guard and bearing cap damage. The LP2 rear bearing and exciter showed damage to a lesser degree. Insulation damage was observed throughout the HP, IP, and LP crossover piping, along with damage to piping hangers and instrumentation.

As the HP and IP rotors were disassembled, it became apparent that liberation of the IP rotor shaft and blade material was the initiating event. Removal of the IP inner cases revealed extensive damage to all stages of the IP rotating blades (Figure 2). The generator end first stage blades were heavily damaged, while the remaining stages were torn off at the airfoil base. A section of the rotor between the 2nd and 3rd stage blades had liberated (Figure 3), including the 2nd and 3rd stage blade roots in that region. The HP turbine flow path was intact. Damage was observed in regions with tight radial clearances between rotating and stationary hardware, such as bearing packing regions and blade tip sealings. The damage observed in the HP turbine was consistent with excessive radial vibrations and / or a rotor whipping event. These observations confirmed that the HP damage was a result of the IP failure, and not vice versa.

The observed IP liberation resulted in significant imbalance and associated vibration of the IP shaft. With steam flow continuing, the liberated material likely migrated to downstream rotor and stationary blades resulting in additional liberation of blades and increased imbalance. The IP imbalance combined with continued steam flow to the entire shaft line, resulted in failure of bearings and their ability to contain the imbalance forces. As a result, considerable damage was imparted to turbine casings, piping systems, and other connected equipment.

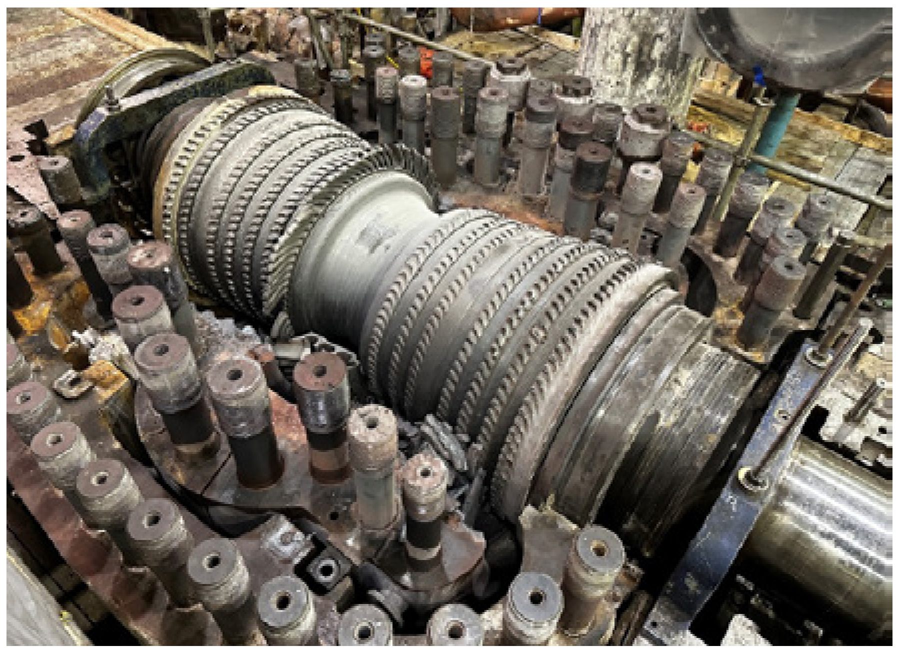


FIGURE 2. IP Turbine Rotor with Inner and Outer Casing Upper Halves Removed

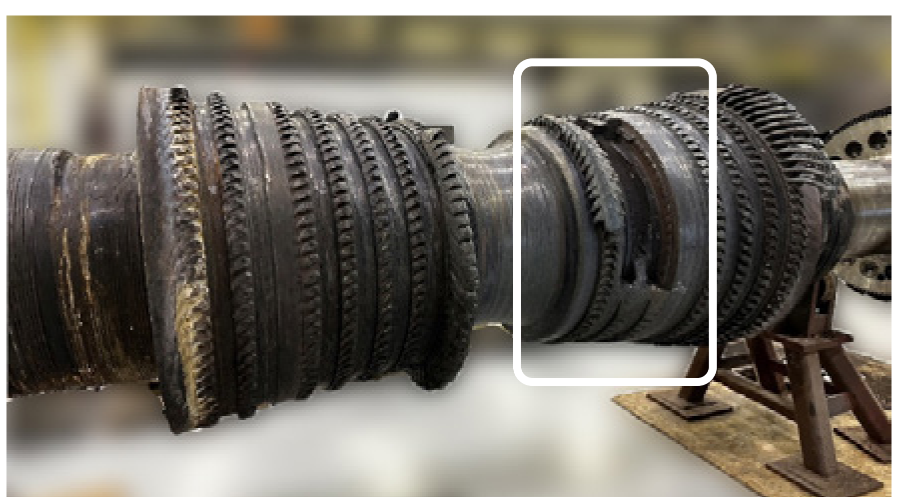


FIGURE 3. IP Rotor Shaft Denoting Area of Liberated Material

SI’s support for this event included:

- An onsite investigation of the turbine components
- Metallurgical evaluation of the damaged IP rotor
- Operational and maintenance review
- Thermal and Structural Analysis of the IP rotor
- Fatigue and creep lifing calculations
- A detailed causal analysis of the event

ROTOR METALLURGICAL EVALUATION

During SI’s onsite inspection, we observed that the IP rotor material between blade rows 2 and 3 detached from the base rotor in an arch of approximately 120 degrees circumferentially. The primary fracture propagated from the outlet side of blade 2 bottom groove and progressed axially to the inlet side of blade 3 bottom groove (Figure 4). Secondary fractures radiated from the inlet blade 3 hook fitting and progressed axially toward the outlet blade 2 hook-fitting, radially through the wheel post hook, and at the ends of the liberated material.

Visual examination of the primary fracture surface shows an aged crack that progressed over time. Closer visual examination confirmed that the oldest surface was at the blade 2 outlet side. The surface had a “rock candy” appearance, which is a telltale indication of a creep driven failure.

SI’s evaluation was based on visual and photographic examination of the rotor body and laboratory metallographic evaluation of the liberated rotor remnants whose mating surfaces were traceable. Due to post failure tumbling of the liberated material, the primary fracture was mechanically deformed at the inlet side, obscuring much of the fracture initiation region. However, evidence of creep cracking and bulk creep voids necklacing the grain boundaries was readily apparent (Figure 5). An oxide layer was observed further to the interior where post failure damage was absent. Grain boundaries at the initiation region exhibited significant deformation, consistent with post release tumbling damage.

An undisturbed crack in the 2-3 post was mechanically opened and subsequently cross sectioned for metallographic analysis. Because the crack was closed, most of the initiation side (outlet side) was protected from post-failure impacts. Consequently, the initiation side provided good details on the state of the material in the affected region. As with the primary fracture, there was evidence of creep cracking, with fissuring and bulk creep voids necklacing the grain boundaries. A thick oxide layer was prominent at the initiation side and attenuated into the interior.

FIGURE 4. Primary Fracture Location

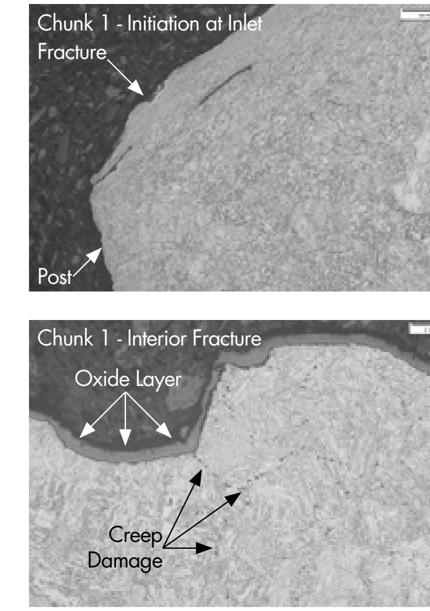


FIGURE 5. IP Rotor Chunk 1 – Photomicrograph Showing Initiation Area and Interior of Primary Fracture

To quantify the fracture surface age, the protected secondary fracture surface was metallurgically examined, and oxide thickness measured. The average of the thickest areas was determined to be 6.8mils. SI utilized research data for 12 Cr steel that characterizes typical oxide growth over time to compute the approximate age. Oxide correlations were plotted for a range of measurements over a temperature range centered around SI’s predicted 930°F at the secondary fracture location. From this data, SI estimated the crack age as between 50,000 and 100,000 hours of service.

All units at this site have experienced increased cycling in recent years, consistent with much of the US fleet. The IP rotor, in service since initial commissioning, had accumulated approximately 550 starts, with the majority of those events imposed

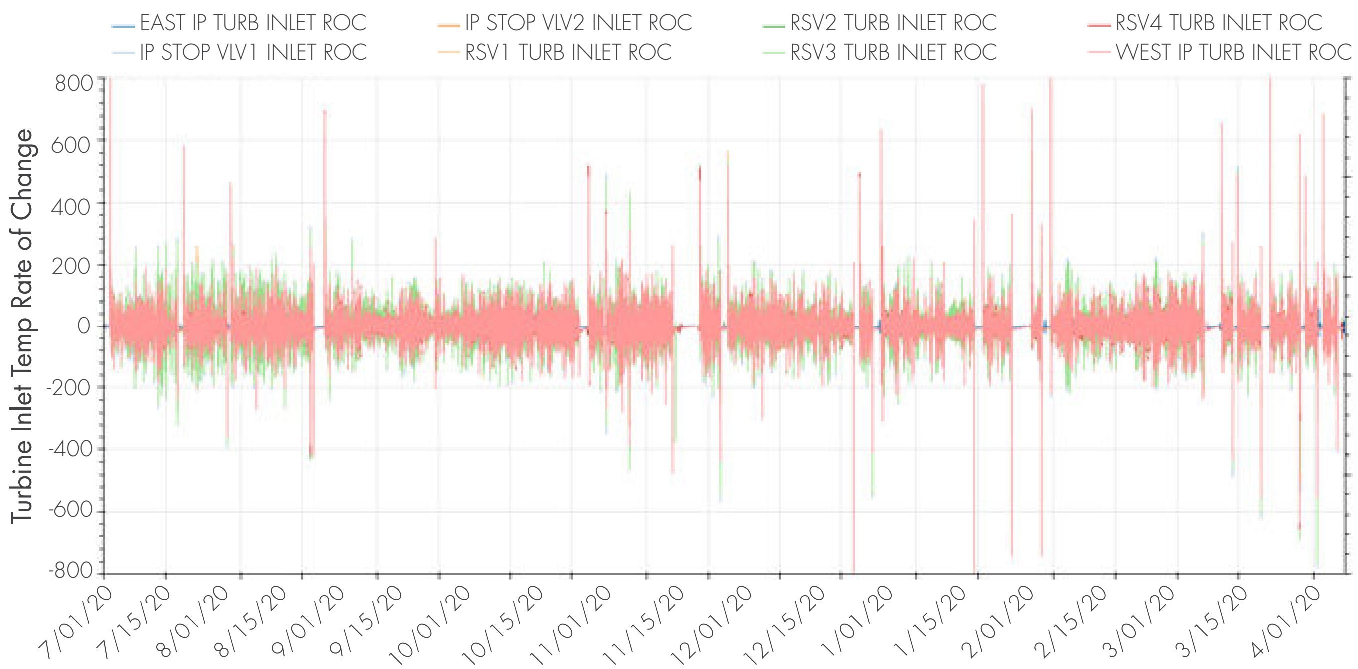


FIGURE 6. JEC 3 IP Steam Temperature Rate of Change (°F/hr.)

in the last 10 years. With increased cycling, fatigue related damage and/or creep-fatigue (CF) interactions can significantly influence the operating life of an aging rotor.

CF interactions can range from fatigue dominated to creep dominated. In fatigue dominated CF, cracking will be intergranular (as was observed), with little creep cavitation and grain boundary voids remote from the crack region. In the creep dominated CF, notable grain boundary void accumulations are typically observed remote from the crack(s). This latter case is more consistent with the observations from the IP rotor. Although creep appears to be the dominant mechanism for crack growth, mechanical fatigue likely contributed to crack growth rates, particularly in low-cycle regions due to unit cycling.

OPERATIONAL AND MAINTENANCE REVIEW

A review of the prior 3 years of operating data was performed, unit ramp rates and operating temperatures. The Rate of Change (ROC) in degrees per hour was plotted for all three units over a three-year period (Figure 6). The data identified rapid temperature changes during shutdowns and startups, with an incremental ROC of 133°F within a 10-minute period occurring regularly. Turbine manufacturers (OEMs) typically limit ROC to less than 50°F within a 10-minute period. Although cycling has imposed high ROCs, no metallurgical evidence was identified to indicate that cycling influenced or was the root cause of the IP rotor failure. However, it is reasonable to postulate that the CF interaction accelerated the primary fracture propagation rate. The effects of rapid startups may have a greater impact on components with less capable materials, such as the HP and IP turbine casings, the steam piping, and potentially the boilers themselves.

During the previous major outage where the IP rotor was removed, a crack was found on the generator end first stage inlet side blade slot bottom. Blade lift and looseness has been identified on the generator end first stage, prompting blade removal and subsequent identification of the blade slot cracking. The liquid penetrant test identified 3 total cracks, two near the bottom of the blade slot and one near the edge of the blade contact surface. A volumetric inspection of the solid inner portions of the rotor was performed; however, non-destructive examination (NDE) was NOT performed for the adjacent blade slots to inspect for similar cracking as that identified within stage 1.

LIFING ANALYSIS OF THE IP ROTOR

A finite element analysis (FEA) model of the IP rotor was developed from available/collected rotor dimensions. To investigate the correlation between operating temperatures and metallurgical findings, steady state, full load operating temperatures were calculated using blade geometry and the supplied heat balance diagram. The first stage blades were an impulse style design with the remaining stages configured as reaction style blades. Based on the blade style and flow path cross sectional areas and radial position, stage pressure ratios were calculated. Utilizing the heat balance and pressure ratios, steam energy balance calculations were iteratively solved to generate stage-by-stage temperatures and pressures.

The OEM supplied stage temperatures would predict the 3rd stage rotor region to operate below 900°F, and underpredicted steam temperatures at downstream extractions. SI's calculated temperature profile better aligns with measured extraction and exhaust temperatures. Similarly, the 2-3 post predicted temperatures increased by approximately 30°F as compared to the OEM provided predictions (Figure 7). Steady state operating stresses were calculated to assist with lifing calculations (Figure 8). The results indicate the highest predicted elastic only stress is at the forward stage 3 hook where cracking was observed in the metallurgical analysis.

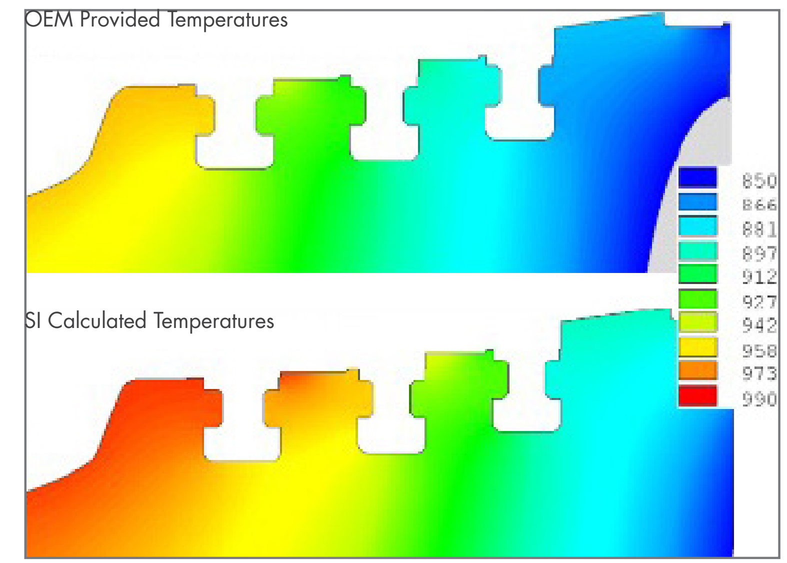


FIGURE 7. IP Rotor Generator End, Forward Stage Temperature Predictions

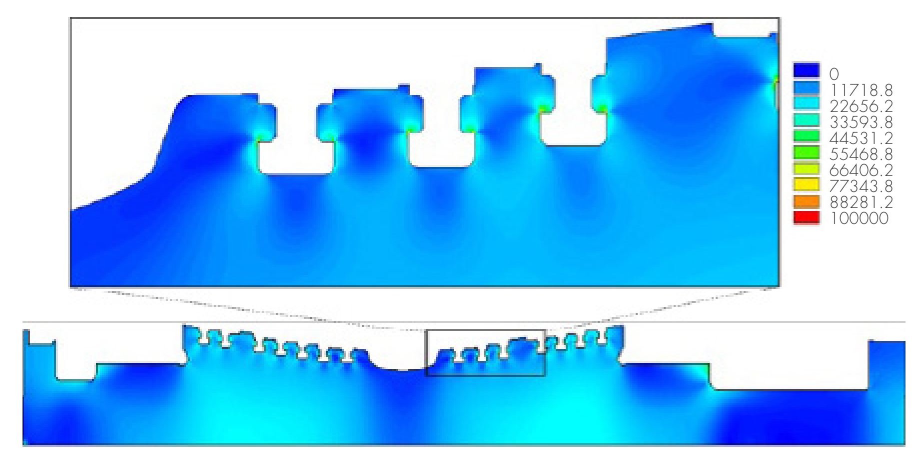


FIGURE 8. IP Turbine Steady State von Mises Stress Predictions

To support the estimation of creep rupture timeframes for key locations in the IP rotor, Wilshire curves were fitted to industry available 12 Cr rotor steel data. At high exposure hours (>100K hours), changes in the material microstructure can alter the mathematical trend of time-to-creep rupture versus applied stress. Thermal aging is a phenomenon corresponding to long-term, irreversible changes in the structure, composition, and morphology of a material when exposed to operational temperatures. In 12 Cr steels, thermal aging results in a reduction in the yield and ultimate tensile strengths, as a function of exposure time and temperature, and may cause a reduction in time-to-creep rupture at high exposure hours. The Wilshire Model was modified to account for aging effects and minimize extrapolation uncertainty beyond 100K operating hours (Figure 9).

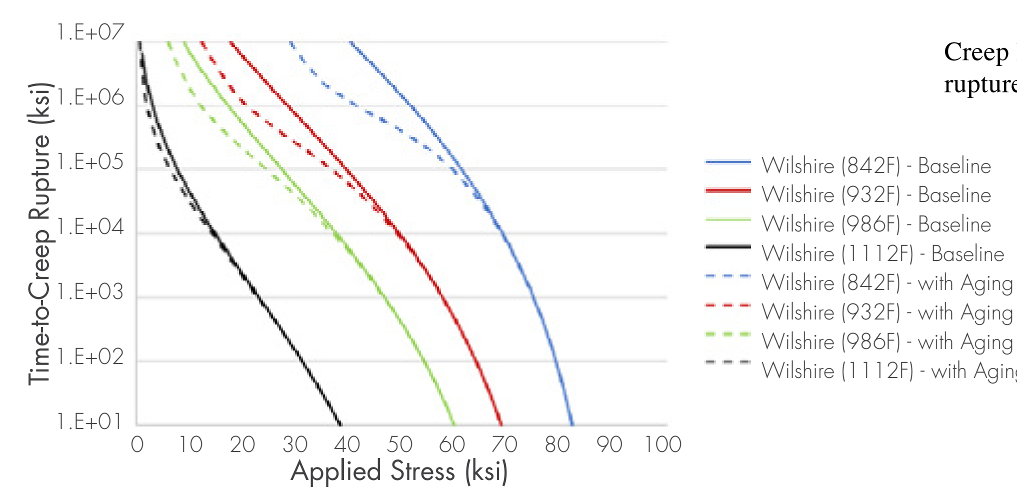


FIGURE 9. Comparison of Baseline Wilshire Curves to Wilshire Curves Corrected for Extrapolation Uncertainty

Creep life predictions (time to creep rupture) were performed along two key paths within the IP rotor: 1) the first stage inlet side blade slot bottom, and 2) the 2-3 post path consistent with the event material liberation. Due to the multiaxial nature of the stresses in the IP rotor, as compared to the applied stresses during creep rupture testing, a modified Hayhurst-Huddleston approach was taken to collapse the principal stresses into a stress value to be used in the creep rupture model (Figure 10).

The resulting creep rupture inclusive average and minimum (approximating 3σ) life predictions were compared for the first stage inlet side blade slot bottom and 2-3 post event path. While the 2-3 post's stress magnitude was greater, the first stage inlet side blade slot is predicted to operate approximately 50°F hotter resulting in a significantly shorter time to creep rupture. The resulting predictions for the first stage inlet side blade slot suggest an average life of 210,000 hours, with a minimum creep rupture prediction as early as 55,000 hours. The minimum creep rupture prediction for the 2-3 post was calculated as early as 250,000 hours.

DETAILED CAUSAL ANALYSIS

A detailed causal analysis was completed by SI's team in support of the RCA. This investigation included:

- A detailed review of the metallurgical findings performed on the IP rotor material:
  - Tertiary creep voids and creep cracking were identified in multiple 2-3 post features.
  - There were no observed metallurgical features indicative of cycling influenced crack initiation.
  - Surface oxidation indicates that both the primary fracture and radial hook cracks were present during the prior rotor out major outage.
- Analytical and empirical correlations of first stage inlet side blade slot cracking:
  - Re-evaluation of metallurgical samples performed during the first stage repair in the prior major outage (243,000 hours) indicate the rotor had experienced advanced creep damage with chains of grain boundary creep voids present.

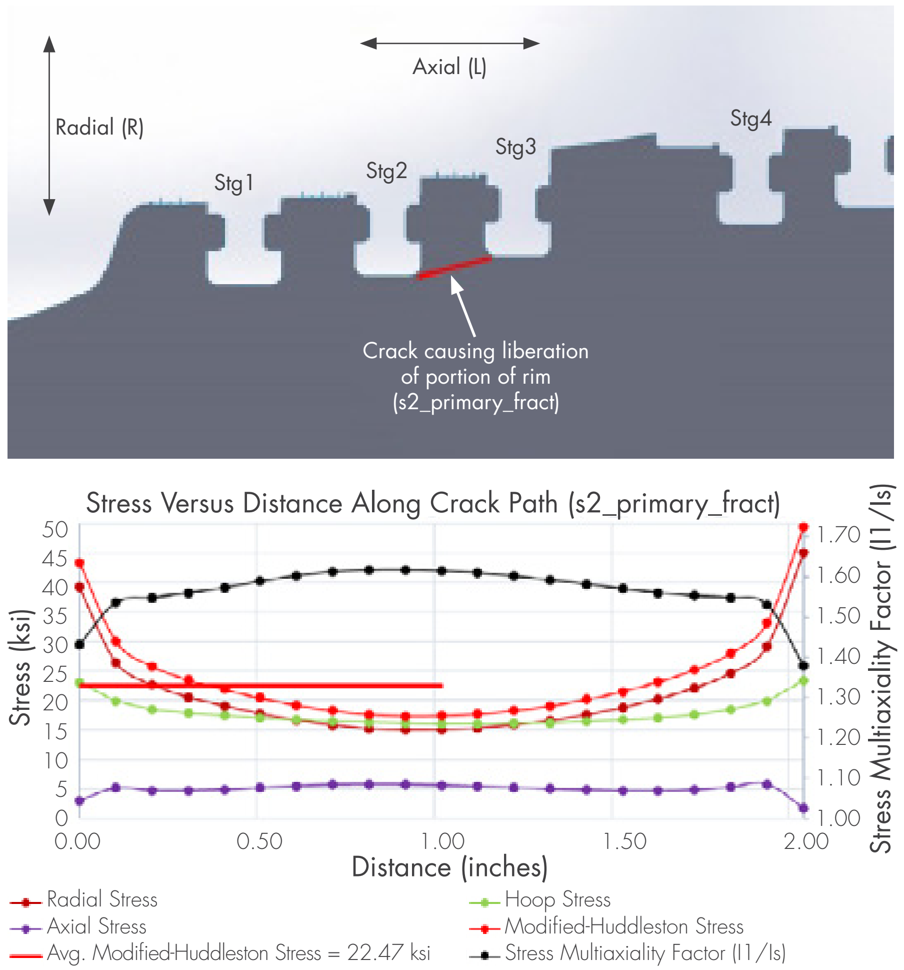


FIGURE 10. Predicted Stresses and Multiaxiality Factor Along Primary Failure Path

  - Evaluation of sister IP rotors onsite indicated that similar first stage cracking had been historically experienced between 140,000 and 199,000 hours of operation.
  - This rotor configuration has experienced significant creep degradation in less than 200,000 hours of operation. The stage 2-3 post, located about 6 inches axially downstream, operates under slightly reduced temperatures and comparable stress levels.
- The metallurgical evaluation did not identify any evidence to suggest that unit cycling influenced the IP rotor event. It is reasonable to postulate that the CF interaction accelerated the primary fracture propagation rate; however, cycling was not a root cause of the event.
- Prior outage inspection and fitness for service assessment:
  - During the major outage and repair, IP first-stage cracking was identified upon removal of the blades. Volumetric NDE inspections were performed, however, this inspection was not focused in such a way that stage two and three blade slot indications would have been captured. With the age of the rotor and the crack findings in the first stage slots, the inspection of the adjacent slots should have been performed.
  - Evidence of creep related damage was available to the service provider, however, miss-judgement of the damage mechanism led to an assumption that the rotor was serviceable without additional testing or inspections.
  - No lifetime type evaluation was performed, and no rotor life prediction was available.
  - It was recommended to re-inspect the first stage repair after 50,000 hours, but no similar guidance was provided for the remaining stages.

Through this causal analysis, the steam turbine event was determined to have occurred because of the liberation of a portion of the IP rotor stage 2–3-wheel post. The partial IP rotor wheel post liberation resulted from advanced creep degradation of the wheel post material. This creep occurred under prior and continued operation at normal operating temperatures and stresses beyond the capability of the rotor. The IP rotor remained in operation beyond its capability for two primary reasons.

1. The owner of the equipment did not have a documented rotor life (i.e., completion of either an original or post service life assessment).
2. The service provider communicated that the rotor could operate for 50,000 additional hours without the completion of a life assessment (the event occurred after approximately 26,000 hours of operation).

SI'S VALUE AS AN INDEPENDENT PARTNER

In support of the described event, SI provided a detailed, independent root cause analysis, and recommendations for corrective and preventative actions. In addition to the event assessment, SI developed customized inspection plans for the remaining units at the site and fleet risk management and inspection plans.

CUSTOMIZED INSPECTION FOR THE REMAINING UNITS

During the investigation, as the metallurgical degradation of the IP rotor was understood, SI performed a risk assessment of the two sister units (3 total IP rotors, including a spare - Figure 11). Inspection of the first stage blade slot cracking was inconsistent (having never occurred for one of the two operating rotors, and more than 100,000 hours previously for a rotor with previous repairs). Similarly, inspection of the 2-3 post slot region had never been specifically performed.

Where inspections had previously occurred based on blade lift measurements during planned outages, SI utilized basic rotor cross section geometry to develop a NDE method for inspecting both the forward and aft blade slot geometries for the first 3 stages per flow. The site took advantage

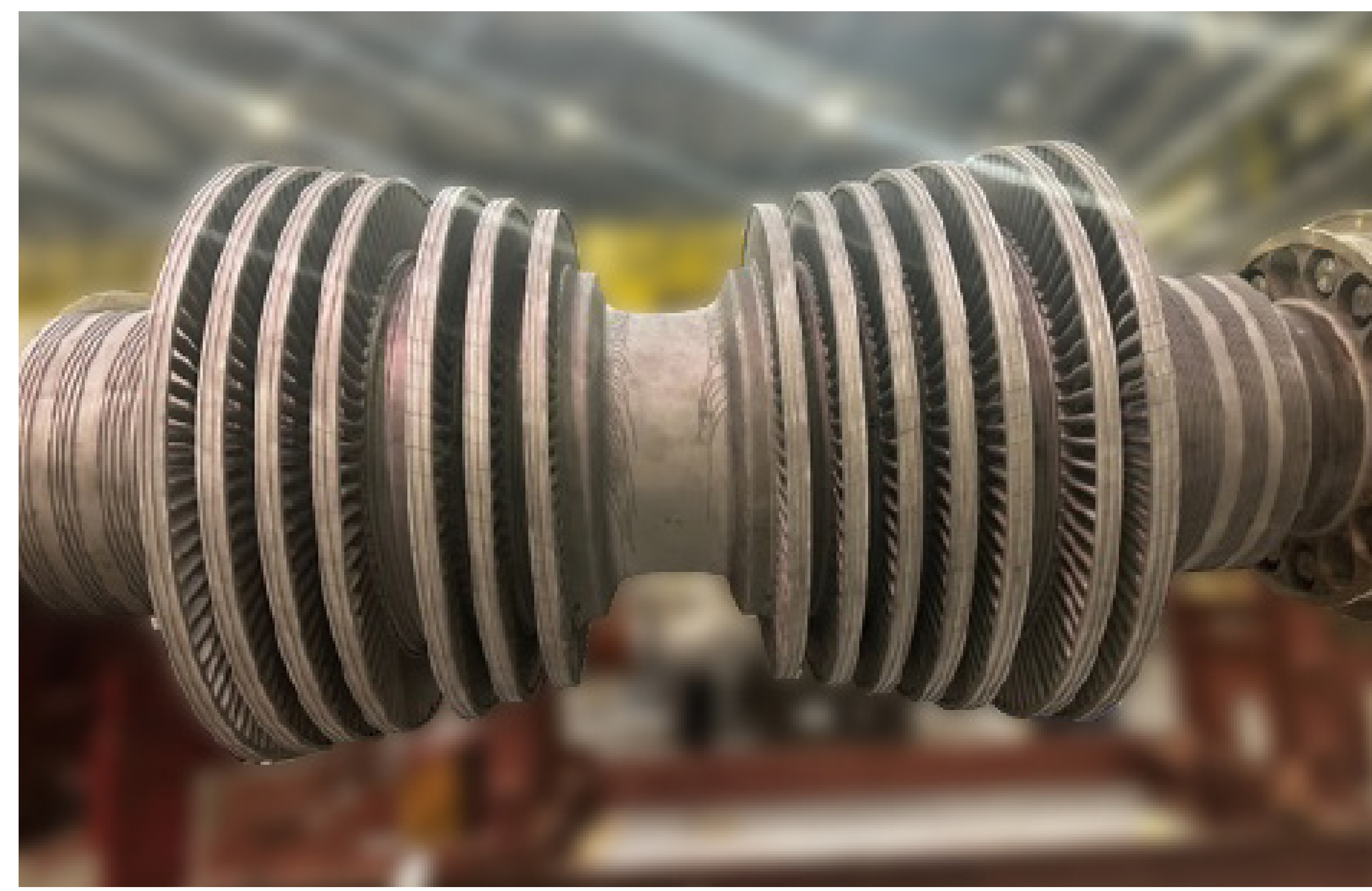


FIGURE 11. Inspection of Sister Unit IP Turbine Rotor

of market outages to disassemble the two sister IP turbines and removed the rotors for inspection. The first IP rotor, which had previously had a stage one post weld repair performed, remained clear of any service induced damage in stage 1 through 3 slot regions. The second rotor, which had no prior repairs, was identified to have first stage slot cracking later confirmed by penetrant testing with the blades removed (Figure 12).

SI helped the site manage the risk of continued operation of its existing aging assets through minimally invasive NDE inspections tailored to suit its geometry and operating profile.

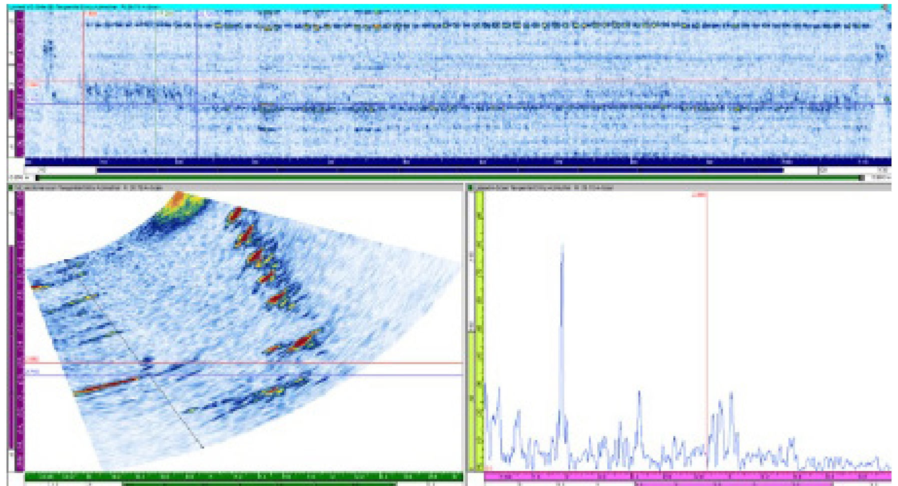
FLEET RISK MANAGEMENT AND INSPECTION PLANNING

To support the utility's remaining aging fleet, SI performed a fleet risk assessment of its remaining large steam drivetrains.

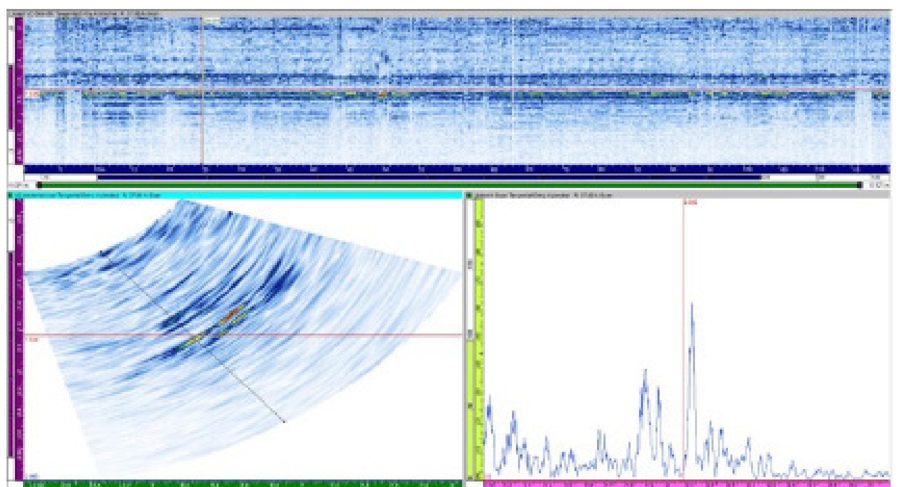
This assessment includes an evaluation of each rotor including:

- Total hours and starts
- Quality of Inspections and Operation Since Last Inspection
- Operating conditions (steam temperature and quality)
- Operating Stresses
- Rotor Construction:
  - Forging vintage and material specification requirements
  - Crack tolerance and impacts of aging effects
- Operation based degradation modes:
  - Time dependent modes (Creep Rupture, Stress Corrosion Cracking, etc.)
  - Cycles dependent modes (Fatigue, etc.)

The fleet risk assessment provided risk rankings for each degradation mode as well as rotor specific and unit specific risk. The assessment identified fleet outliers based on embrittlement susceptible forgings as well as previously deferred maintenance inspections.



Filename:	Generator End Stage 1 Admission wheel
Analysis:	Incipient service induced damage noted at approximately 4.64″-18″ CCW from Number 1 loading slot with a thru-wall extent of 0.125″.



Filename:	Generator End Stage 1 Discharge side
Analysis:	No apparent service damage detected.

FIGURE 12. LPA Results from Sister Unit IP Rotors (Left: Damaged, Right: Clean)

As rotors age beyond their design operating period, operating intervals should be re-evaluated based on rotor and material specific degradation modes and desired operating profiles. Accumulated damage from operating hours and startups combined with material aging effects will degrade material capability and reduce tolerance to service induced damage.

Rotor inspection prioritization by risk and optimization by degradation specific modes and locations can keep assets operating safely and support reasonable outage planning and replacement timelines. An informed rotor life management approach probabilistically accounts for short- and long-term rotor degradation in future re-inspection intervals, inspection scopes and risk planning.

Life Extension of Raw Water Piping through Life Cycle Management Practices

ADAM ROUKEMA
aroukema@structint.com

For nuclear power plants, service water (raw water) systems play a critical role in plant safety and reliability. These systems are responsible for providing shutdown and emergency cooling of the reactor, but they are also among the most vulnerable to degradation over time. Exposure to raw water leads to corrosion, biofouling, and material loss, all of which can compromise the system's integrity. Any loss of functionality, from localized wall thinning to through-wall leakage, can render the system "inoperable" and may lead to unplanned outages or additional regulatory scrutiny.

As U.S. Nuclear plants pursue extended operating licenses, operators must maintain fitness for service of their raw water piping well beyond its original planned life. However, predicting the location(s) and extent of potential degradation is challenging. Comprehensive inspection of every pipe segment is impractical, constrained by accessibility (large portions of the system may be buried) and associated cost. Traditional inspection methods, such as gridded ultrasonic (UT) thickness measurements from the piping OD, may not adequately characterize the difference between generalized wall thinning and localized pitting. Specialized corrosion mapping tools exist, but they often identify multiple areas below the ASME Code-mandated minimum wall thickness (t_{MIN}), leading to urgent engineering evaluations and disposition.

These challenges can be successfully addressed through employing a more strategic and predictive approach. By integrating advanced flaw evaluations, corrosion rate assessments, and risk-based prioritization, raw water system owners can make informed, proactive decisions that reduce inspection cost, avoid unplanned emergencies, and extend asset life. This article introduces SI's Life Cycle Management (LCM) approach for raw water systems, a structured methodology that shifts the focus from numerous inspections and reactive findings to data-driven asset management.

OVERVIEW OF LCM APPROACH

The traditional approach to raw water system management follows a straightforward cycle, as illustrated by the red path in Figure 1. In theory, this process should provide a structured means of maintaining system integrity. However, in practice, the **Planning** stage is often underdeveloped, focusing more on scheduling exams rather than proactively assessing risk and degradation trends. As a result, **Inspections** frequently uncover unexpected degradation, forcing plants operators into a reactive mode. Rather than being a controlled decision-making process, the **React** stage often leads to last-minute engineering justifications, unplanned replacements, increased cost, schedule impacts, and regulatory scrutiny. This cycle of

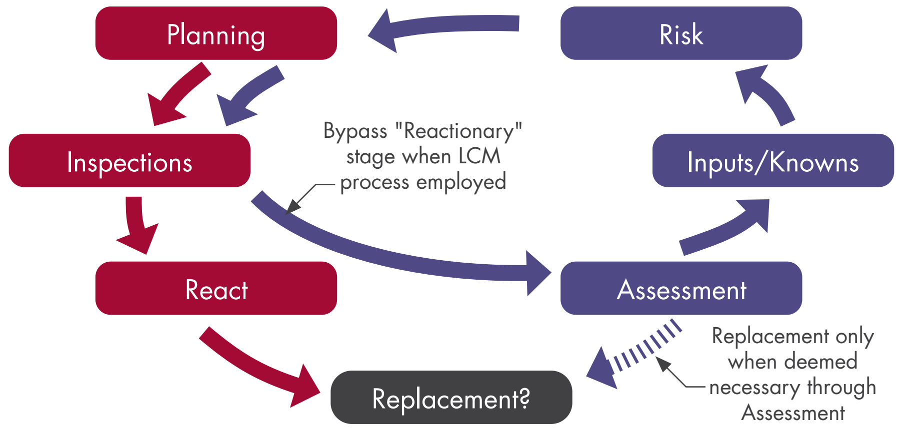


FIGURE 1. Graphical Overview of Recommended LCM Approach

"inspect and react" creates unnecessary risk and inefficiency, highlighting the need for a more predictive and strategic approach.

SI's recommended LCM approach adds a series of optional yet impactful steps to the traditional inspection process. As shown by the purple path in Figure 1, the process introduces three key elements – **Inputs/Knowns, Risk, and Assessment** – the latter of which replaces the **React** stage from the traditional process. By leveraging existing system data and a structured risk assessment, **Planning** is optimized to ensure **Inspections** are targeted where they provide the most value, reducing unexpected findings. Crucially, this process is cyclical – new information gained from inspections is treated as an opportunity to refine future assessments and improve decision-making.

The first step, **Inputs/Knowns**, collates available system data for downstream use in risk assessment and inspection planning/optimization. The LCM process systematically catalogues information related to historical performance, structural margin, degradation trends, and potential consequences, an overview of which is provided in Figure 2.

- **History**: Prior inspection and evaluation results, chemical treatment records, and replacement history highlight known problem areas and inform expectations for future performance.
- **Structural Margin**: The available margin between current wall thickness and the minimum allowable thickness (t_{MIN}) is the foundation for LCM serviceability assessments. Tools such as thinning handbooks and detailed finite element analysis (FEA) models can justify acceptance of localized thinning that is below t_{MIN}.
- **Degradation**: The rate and distribution of material loss – including both generalized corrosion and localized pitting – are also critical inputs to the LCM process. Advanced statistical models can help quantify expected material loss over time throughout the system. Permanently installed monitoring, such as g-PIMS or spray-on sensors, can help further refine these predictions.
- Consequence: The impact of degradation and associated loss of integrity can have implications well beyond engineering and inspection. Regulatory compliance, operational restrictions, and financial costs must be factored into decision-making.

SI has developed specialized tools to provide additional insight during the Inputs/Knowns stage, enabling more accurate predictions and better-informed decision-making. Several key elements, previously highlighted In Figure 2, are summarized below:

- **Extent of Corrosion (EoC) Evaluations**: SI's proprietary statistical corrosion model uses design and operating information and historical inspection data to predict corrosion rates across an entire system rather than relying on conservative assumptions or isolated inspection points. The output of the model is illustrated in Figure 3, which shows a Degradation Evolution Projection (DEP) curve predicting wall loss and expected failure timelines.
- **Thinning Handbooks**: Rather than treating isolated thinning below t_{MIN} as an automatic failure, thinning handbooks provide pre-established acceptance criteria for localized wall loss. Developed using Finite Element Analysis (FEA) and/or fracture mechanics, handbooks help justify continued operation for degraded components by quantifying remaining structural capacity under expected loads. Figure 4 presents an example of an FEA-based thinning assessment.

SITE PRESERVATION	STRUCTURAL MARGIN	DEGRADATION	CONSEQUENCE
▪ Inspection Results ▪ Prior Evaluations ▪ Chemical Treatment / Biofouling (BG5) ▪ Replacement History	▪ t_{MIN} Calcs (by-Span/By-Node) ▪ Thinning Handbooks ▪ Detailed FEA Models ▪ Leak Tolerance (CC N-513)	▪ Assumed Corrosion Rates ▪ Trends (from Inspections) ▪ Statistical Models (EoC) ▪ Local Corrosion Monitoring (g-PIMS, Spray-On, etc.)	▪ Regulatory (NRC/EPA) ▪ Operational (LCO) ▪ Cost of Repair/ Replacement

FIGURE 2. Key Inputs/Knowns for Raw Water System Management

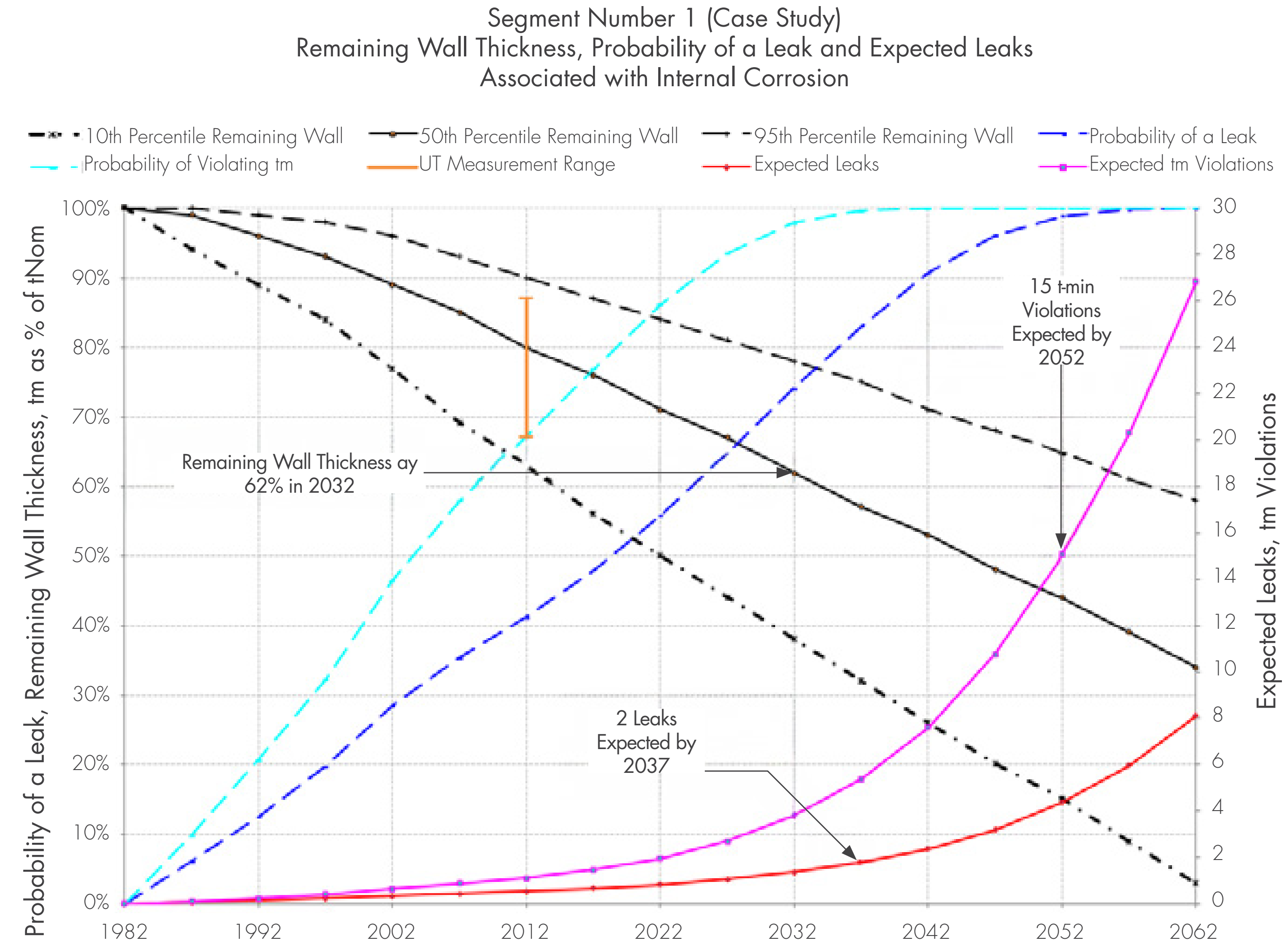


FIGURE 3. DEP Curve from SI's EoC Statistical Model

- **Biocide Monitoring (BG5)**: SI has developed an **online biofilm growth detector, BG5**, which helps optimize biocide application to minimize microbiologically inducted corrosion (MIC). For more information, refer to page 68.

Risk assessment is a critical step in the LCM process, ensuring that inspections and maintenance efforts are prioritized based on both likelihood of degradation and potential consequences. Unlike traditional methods that rely on historical failures or system owner's judgement, a risk-based approach integrates system data, historical performance, and operational conditions to refine inspection strategies. By considering factors such as corrosion rates, structural margin, and consequence of failure, system owners can focus resources where they are needed most.

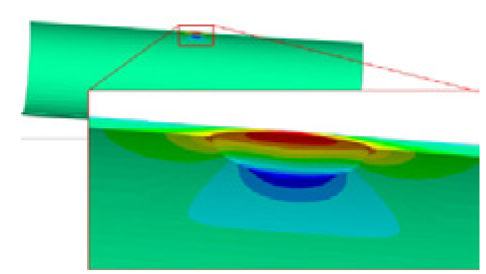


FIGURE 4. Thinning Handbook – FEA Approach to Gain Additional Localized Margin

Effective **Planning** builds on the **Risk** assessment process, ensuring inspections are targeted based on assessed risk, historical data, and engineering insights versus arbitrary schedules or assumptions. The LCM approach eschews the traditional "guess and check" approach by using a structured framework that preemptively accounts for known degradation patterns and risk factors. This leads to fewer unnecessary inspections and ensures that when inspections do occur, they provide meaningful, decision-driving data.

The **Assessment** stage avoids reactive decision-making by ensuring that findings are carefully evaluated before committing to repair or replacement. If an inspection reveals degradation beyond initial acceptance criteria, that does not automatically necessitate intervention. In many cases, the LCM approach can leverage enhanced analysis techniques, such as thinning handbooks, detailed FEA modeling, or Code-based acceptance methodologies, to justify continued operation. If repair is determined to be required, a well-structured process can guide operators to the correct method to optimize near-term cost with long-term acceptability. By embedding engineering-based decision-making in the **Assessment** stage, the LCM approach reduces unnecessary repairs while ensuring regulatory and operational compliance.

LCM IN ACTION: REAL-WORLD APPLICATION

SI's LCM approach was successfully applied at a U.S. nuclear plant to evaluate the structural integrity and remaining service life of safety-related water piping in the Essential Raw Cooling Water (ERCW) and Auxiliary Feedwater (AFW) systems. The project included several key technical deliverables from the LCM process: a detailed finite element analysis (FEA) of a degraded sweepolet Tee, and a system-wide EoC assessment with inspection prioritization.

Initiating Event: Observed Thinning Leads to Detailed FEA

The plant in question conducted a planned inspection of a 30"x24" sweepolet Tee within the ERCW system, as part of its raw water program commitments. The initial inspection was performed with gridded UT (Figure 5), revealing a thinned area well below the calculated t_{MIN} value. Follow-up inspections were performed using detailed phased-array UT (PAUT) to better characterize the extent and distribution of thinning (Figure 6). SI was requested to perform a detailed FEA assessment to demonstrate additional structural margin.

- A three-dimensional FEM was developed, incorporating non-uniform wall thinning profiles from PAUT data.
- A limit load collapse evaluation was conducted per ASME Code, Section III to determine whether the tee could sustain operational loads without plastic collapse.
- Multiple thinning scenarios were analyzed to evaluate worst-case degradation effects, with additional uniform wall loss applied to determine ultimate failure thresholds.

FIGURE 5. Sweepolet Tee with Gridded UT Markings

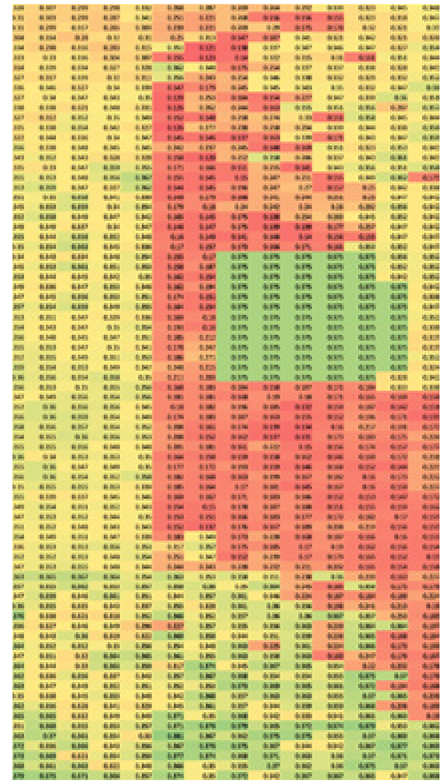


FIGURE 6. Combined UT Results (Manual-Gridded Augmented with Localized Phased-Array)

- Results demonstrated that the degraded tee retained sufficient structural margin under normal, upset, and faulted load conditions (Figure 7), justifying continued operation through the end of licensed life.

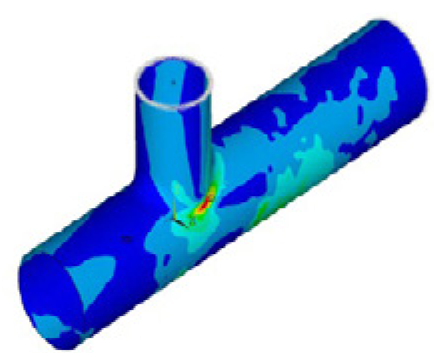


FIGURE 7. Results of Detailed FEA Model (Limit Load Evaluation)

In this example, the plant adopted the Assessment stage of the LCM process, ultimately pursuing an engineering evaluation that prevented unnecessary replacement and avoided a challenging dual-unit outage.

Incorporating LCM: Extent-of-Corrosion and Risk-Based Inspection Prioritization

Following the detailed FEA evaluation, the plant inquired about a more-proactive approach to assessing the potential extent of degradation and integration elsewhere in the ERCW and AFW systems. SI conducted a detailed extent of corrosion (EoC) evaluation to benchmark existing inspection results and optimize future inspection and maintenance strategies.

- The EoC assessment utilized SI's proprietary ACCORDION statistical model to predict degradation rates.
- Inspection data from multiple sources, including PAUT and historical ultrasonic thickness (UT) measurements, was used to benchmark model predictions (Figure 8).
- A risk-based prioritization framework was developed, combining corrosion likelihood and structural margin calculations to rank piping segments by risk level.
- 3D visualization tools were implemented to provide clear, station-wide risk mapping (Figure 9), aiding plant personnel in strategic inspection planning.

This structured LCM approach allowed the plant to shift from a reactive inspection strategy to a proactive risk-informed methodology, reducing unplanned maintenance costs and improving long-term raw water system reliability.

SI Solutions' **Life Cycle Management** (LCM) approach offers a proactive, data-driven framework to optimize raw water system management. This methodology shifts away from the conventional **"inspect and react"** cycle by integrating **risk-based prioritization, advanced flaw evaluations, and predictive corrosion assessments.**

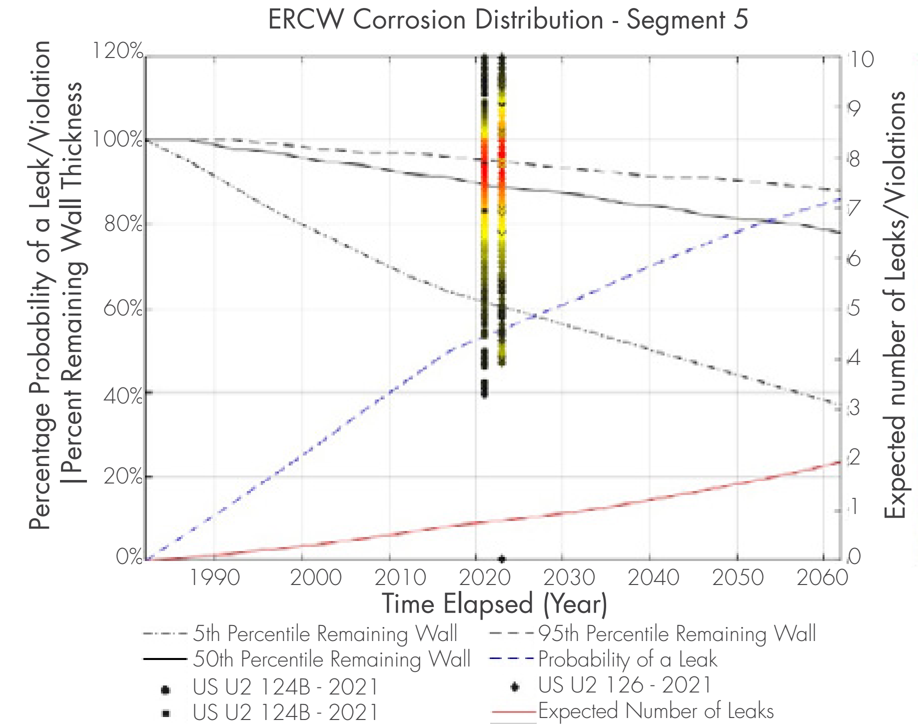


FIGURE 8. DEP Curve Superimposed with Inspection Results

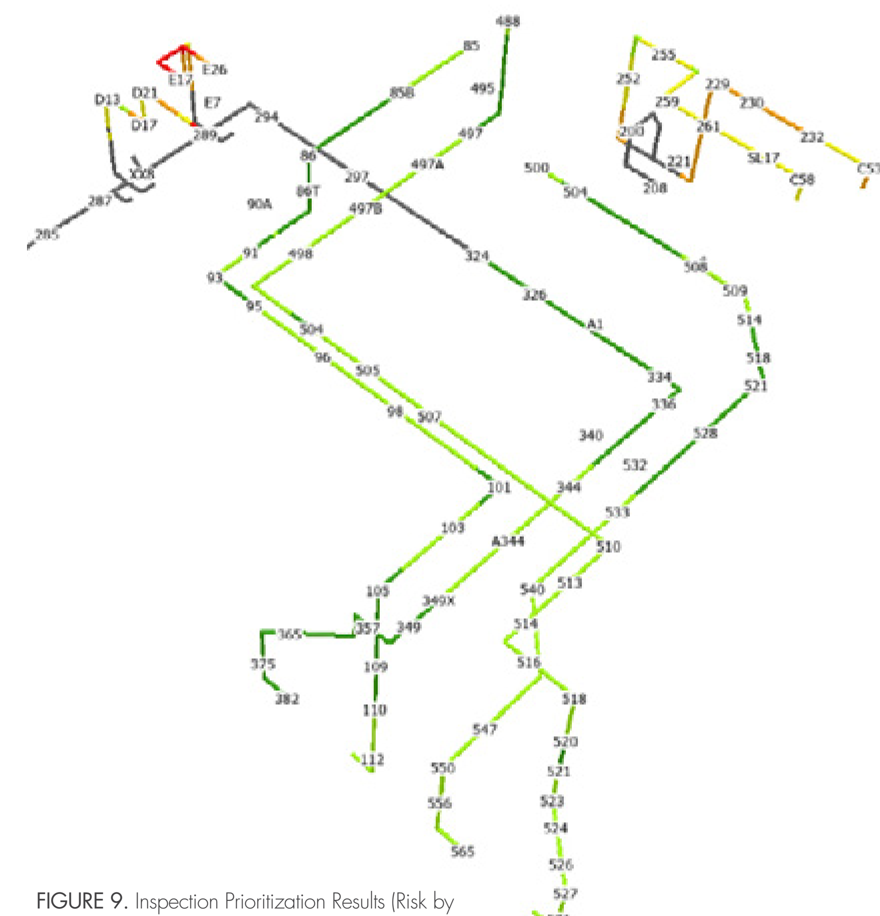


FIGURE 9. Inspection Prioritization Results (Risk by Segment/Node)

Nonintrusive and Robotic Solutions for Tank Asset Management

JASON VAN VELSOR
jvanvelsor@structint.com

Nuclear plant aging management programs require periodic inspections of liquid storage tanks. Traditional inspection methods can be disruptive, requiring tanks to be drained to provide personnel access. SI has developed innovative solutions, including screening techniques that can identify degradation from the tank exterior, and submersible robotics that perform comprehensive NDE without draining. Although initially developed for nuclear applications, these technologies can be employed at conventional power generation, petrochemical, and municipal utility facilities.

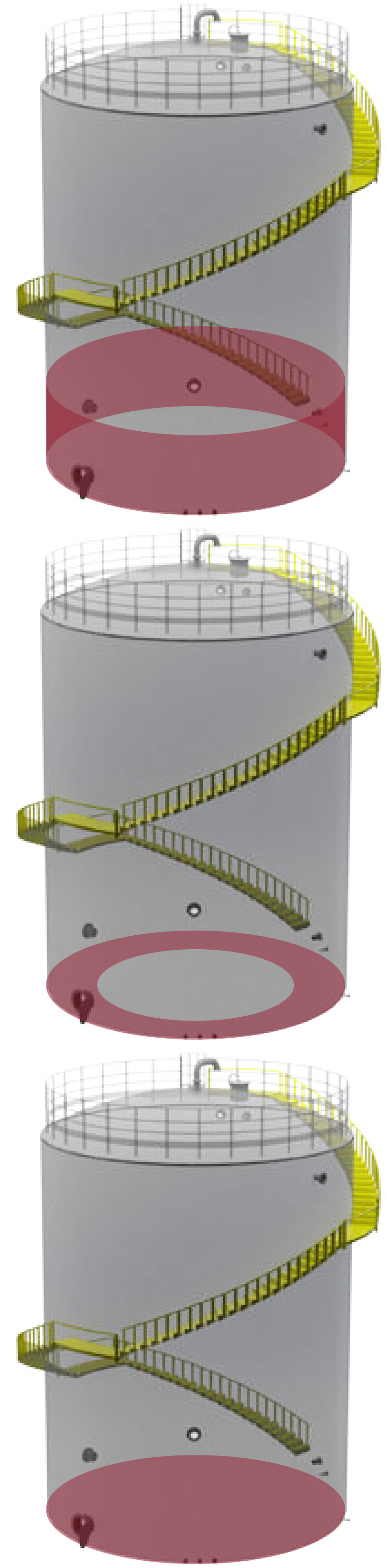
NUCLEAR INDUSTRY GUIDELINES

The nuclear industry established guidelines for integrity management of underground piping and tanks in the early 2000s with the publication of NEI 09-14. More recently, additional constraints have been imposed for plants pursuing life extension, especially for sites applying for subsequent license renewal (SLR) to extend permitted operation from 60 to 80 years. These new requirements for outdoor and large atmospheric tanks are conveyed in the form of specific guidelines for aging management programs (AMPs) within NUREG-1801, Revision 2 and NUREG-2191, Revision 1.

The guidelines within the NUREG documents apply to:

- All metallic outdoor tanks constructed on soil or concrete.
- Indoor metallic storage tanks with capacities greater than 100,000 gallons, designed for internal pressures approximating atmospheric conditions, and exposed internally to water.
- Other indoor metallic tanks that sit on, or are embedded in, concrete, where plant-specific operating experience reveals that the tank bottom (or sides for embedded tanks) to concrete interface is periodically exposed to moisture.
- For utilities with tanks meeting the above criteria, license renewal commitments generally necessitate performing examinations under one of the following three categories:
  - Inspection of the bottom 20% of walls for wall loss and cracking.
  - Inspection of the outer two feet of the floor plates for pitting/cracking.
  - 100% inspection of the bottom floor plates.

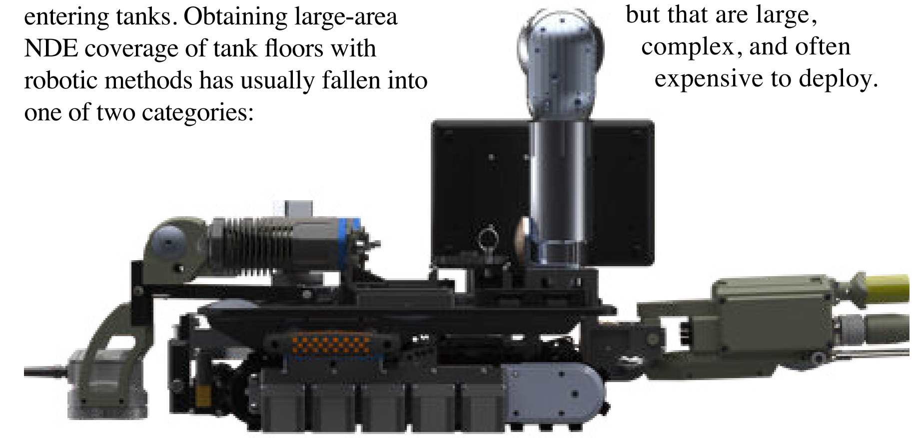
Conducting floor inspections using traditional approaches that require draining and personnel entrance into the tank can be undesirable, given the potential impact on operations, as well as the possibility for certain tanks to contain radiological content. For this reason, many utilities have begun pursuing alternative solutions to safely and accurately perform tank inspections.



TRADITIONAL APPROACHES

Historically, utilities have emptied and entered tanks to conduct manual floor inspections. The scope of these examinations can range anywhere from visual to full volumetric inspection of the tank floor using electromagnetic or ultrasonic techniques. More recently, utilities have attempted to utilize robotically deployed examination methods to avoid emptying and entering tanks. Obtaining large-area NDE coverage of tank floors with robotic methods has usually fallen into one of two categories:

1. Relatively simple robotic systems that deploy traditional NDE sensors for localized measurements, which may take an impractical amount of time to reliably obtain the required coverage, or…
2. Relatively complex robotic systems that deploy a large quantity of traditional NDE sensors to obtain the required coverage more quickly, but that are large, complex, and often expensive to deploy.



Deploying any robotics in tanks is a challenging endeavor, with many practical factors that affect the ease and success of implementation. Several of these factors include:

- **Accessibility** – there are limited access points to the inside of a tank; they are often on top of the tank, and just large enough for a person to fit through.
- **Visibility** – maneuvering within a liquid-filled tank often relies on optical methods, which are impaired or even ineffective in murky or opaque liquid.
- **Navigation** – with poor visibility, continuously tracking the position of a robot within a tank (and hence, the location of acquired data) can be unreliable.
- **Cleanliness** – sediment present in the tank can impair data acquisition and cause additional visibility issues if agitated by the robot.
- **Geometry** – getting complete coverage at the tank edges and around internal features can be challenging or impossible given the size and limited maneuverability of some robotic systems.
- **Tank Size / Inspection Time** – for large tanks, obtaining complete coverage of all in-scope surfaces may require extended scanning time, which can impact operations and delay return to service.
- **Liners/Coatings** – tanks that have been lined with thick coatings such as fiberglass or carbon wrap can render traditional NDE methods useless.

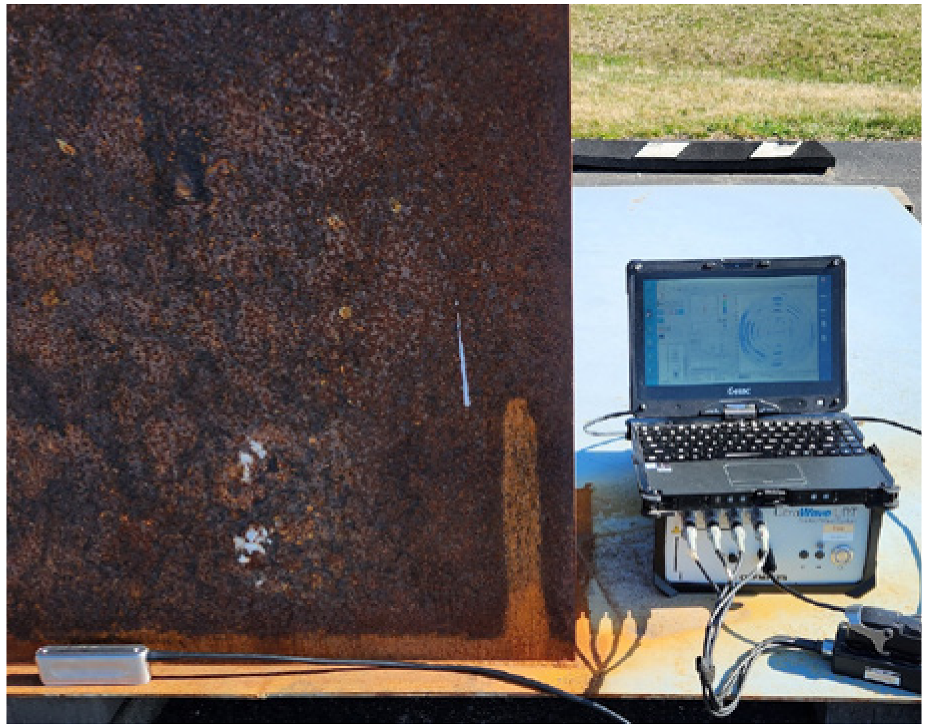


FIGURE 1. GWPA from Tank Chime

SI'S APPROACH

SI offers a suite of engineering and inspection solutions that are designed to help our clients meet their examination commitments while minimizing the associated cost, time, and impact to operations. We work with our clients to determine the required scope of any necessary examinations, based on their Aging Management Program and license renewal commitments, and present a customized inspection approach. Where possible, inspection solutions that can be conducted from outside of the tank are prioritized over approaches that require deploying equipment in the tank. These approaches may include performing pulsed eddy current testing to examine tank walls through insulation or employing guided wave phased array (GWPA) from the tank chime plate to examine the outer annulus of the tank floor (Figure 1).

In situations where putting equipment inside the tank is unavoidable, SI has developed a robotic solution that uses a novel technological approach to provide rapid, 100% volumetric coverage with a range of NDE sensors deployed on a relatively basic robotic platform. Rapid, large-area volumetric coverage is obtained by mapping the tank floor with GWPA testing to identify critical areas (Figure 2). These critical areas can then be investigated using high-resolution, non-contact methods, such as electromagnetic acoustic transducers (EMATs) for UT thickness measurements or SI's dynamic pulsed eddy current technology, SIPEC™ , for dirty or lined tanks.

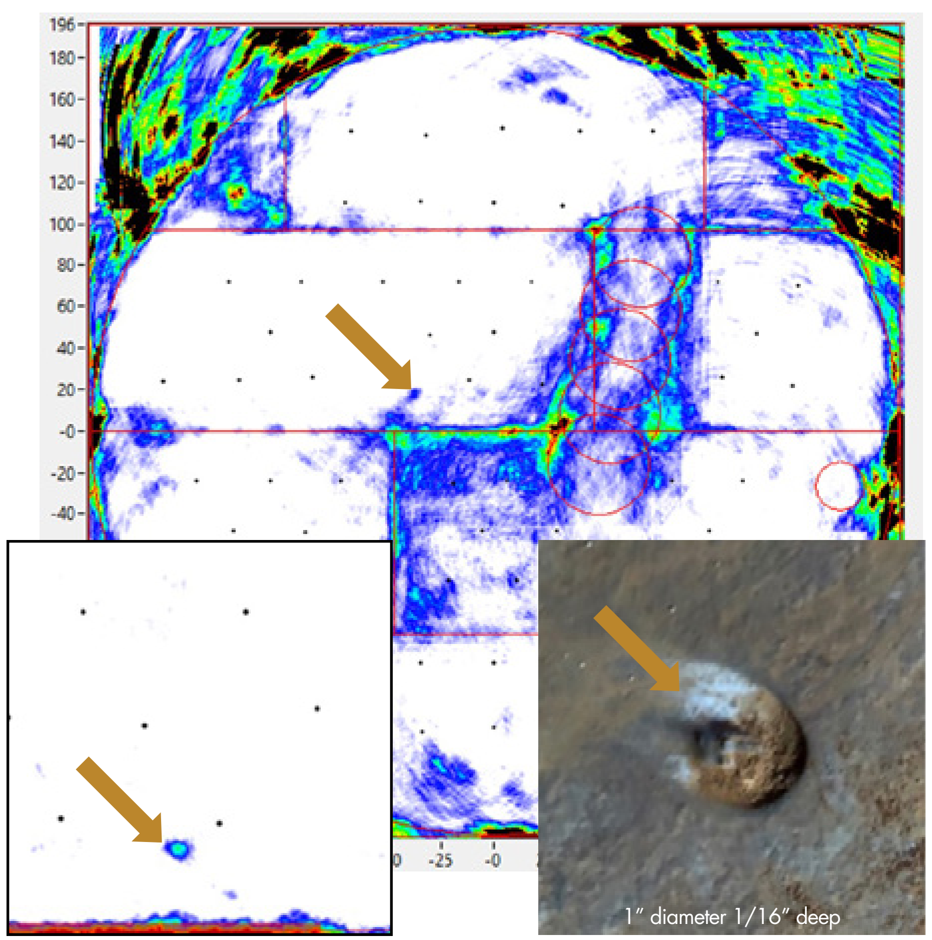


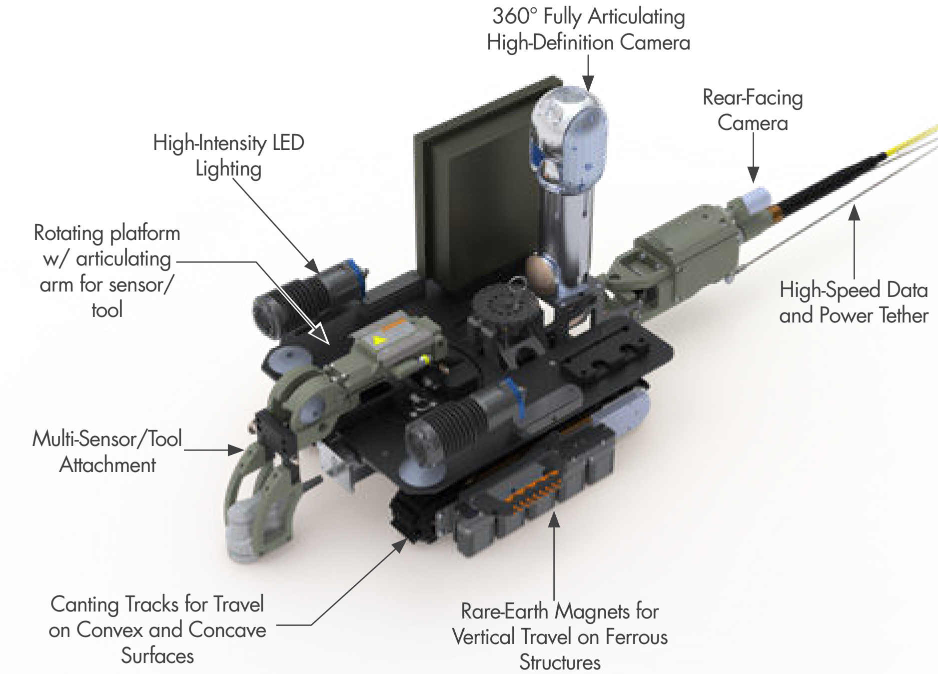
FIGURE 2. GW Phased Array Tank Floor Inspection

From a deployment perspective, SI's robotic system is designed to fit through existing tank access points, can scale carbon steel walls, and can quickly switch between a range of sensor types. Additionally, SI has incorporated a proprietary acoustic vehicle positioning system, where sound pulses track the absolute position of the robot at all times, ensuring precision results and the ability to accurately relocate and rescan specific areas for follow-up activities or future inspections. The acoustic positioning system uses a transmitter placed on the robot and a series of receivers placed on the exterior tank wall to track the movement of the robot. With this approach, positioning is not reliant on visual or other optical methods that can be confounded by cloudy, murky, or otherwise opaque liquid and is not subject to encoder error or drift.

ENGINEERING SUPPORT SERVICES

Beyond inspection, SI provides integrated engineering support that couples directly with tank inspections. SI's expertise includes disposition of findings, detailed evaluation of any anomalies, and optional integration with our piping and tank asset management database, MAPPro™ . SI engineers are adept at employing detailed FEA models and/or fracture mechanics techniques to assess the acceptability of any observed flaws/defects. For time-critical inspections, engineering handbooks can be developed before the examinations to provide real-time disposition of any findings. Loading inspection results into MAPPro enables risk-ranking utilizing time-proven algorithms, thereby informing future programmatic actions.

Using the advanced deployment and inspection technologies highlighted herein, SI is able to comprehensively inspect and disposition findings from tanks of various sizes while reducing schedule risk and ensuring accurate results.



TANK INSPECTION NDE TECHNOLOGIES

- **Guided Wave Phased Array (GWPA)**
  - Used to rapidly inspect large areas such as a tank floor.
  - Provides 100% volumetric coverage in a minimal amount of time and with minimal surface preparation.
  - Identifies critical areas that should be investigated further using more precise examination technology. This follow-up is completed by switching probe heads and conducting targeted quantitative exams.
  - Can also be applied from the chime plate on the tank exterior to examine the outer annulus of the tank floor.
- **Electromagnetic Acoustic Transducer (EMAT) Ultrasonic Thickness Testing**
  - A non-contact (up to 0.25 inches of liftoff) volumetric examination that provides quantitative wall thickness for either carbon or stainless-steel tanks.
  - Electromagnetic sensors generate UT for thickness measurements and are electromagnetically coupled, thus eliminating the need for couplant or close contact with the test surface.
  - This type of testing is helpful for corrosion mapping where surface prep is not possible or costly or if there is a coating/liner present; additionally, it allows for remote robotic inspections, including those where the probe is submerged.
- **SIPEC™ Electromagnetic Thickness Testing**
  - Proprietary non-contact volumetric examination that works through internal liners and sediment (up to several inches) targeting either carbon or stainless steel.
  - Employs a proprietary dynamic pulsed eddy current measurement technique for rapid scanning.
  - Higher liftoff, lower resolution option when compared to EMAT UT.

Materials Lab Featured Damage Mechanism

Creep Fatigue in Steam-Cooled Boiler and HRSG Tubes

WENDY WEISS
wweiss@structint.com

Creep-fatigue is caused by the accumulation of damage through synergistic interaction of cyclic stress and elevated operating temperature. The creep and fatigue components of the damage usually occur at different periods in the thermal cycle to result in a failure with characteristics of both mechanisms. Structural Integrity has an experienced group of materials specialists and a full-service metallurgical testing laboratory that can help with any situation involving material property characterization.

Creep-fatigue is generally assumed to be the active mechanism when the rate of fatigue damage is influenced by the strain rate and hold times while the tube is operating at temperatures within its creep regime.

MECHANISM

Creep-fatigue is essentially the accumulation of damage through synergistic interaction of cyclic stress and an elevated operating temperature. The creep and fatigue components of the damage usually occur at different periods in the thermal cycle. Cyclic loading may occur at temperatures within the material's creep regime (≥800°F for Cr-Mo tubing). Once steady state conditions are reached, the component may continue to be exposed to high temperatures and localized stresses, which can result in the accumulation of additional plastic strains due to creep. Furthermore, if residual stresses due to thermal transients were present, creep relaxation would add to the magnitude of the inelastic strain. The key takeaway regarding creep-fatigue damage is that the fatigue life can be significantly less than would be predicted from pure fatigue test data.

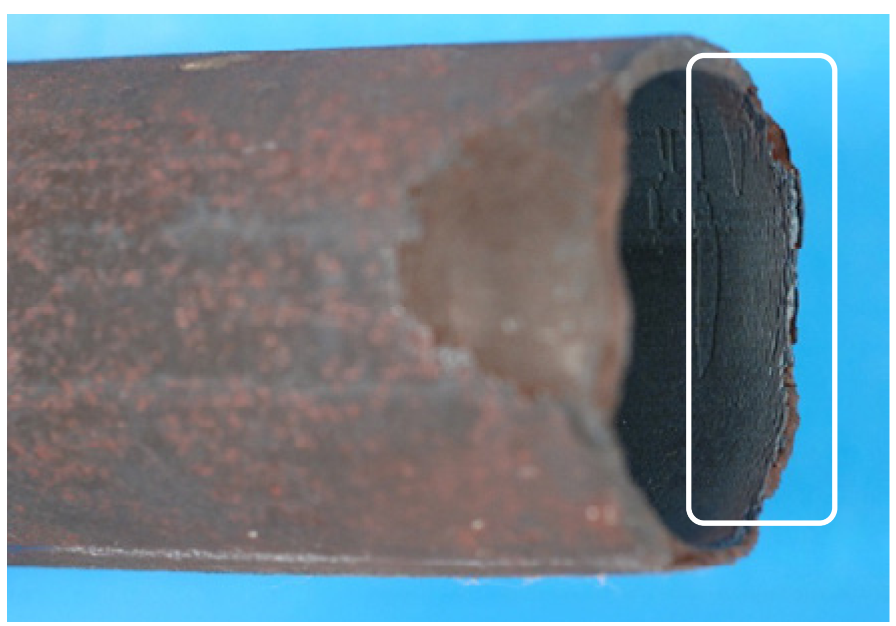


FIGURE 2. Tube to header weld crack.

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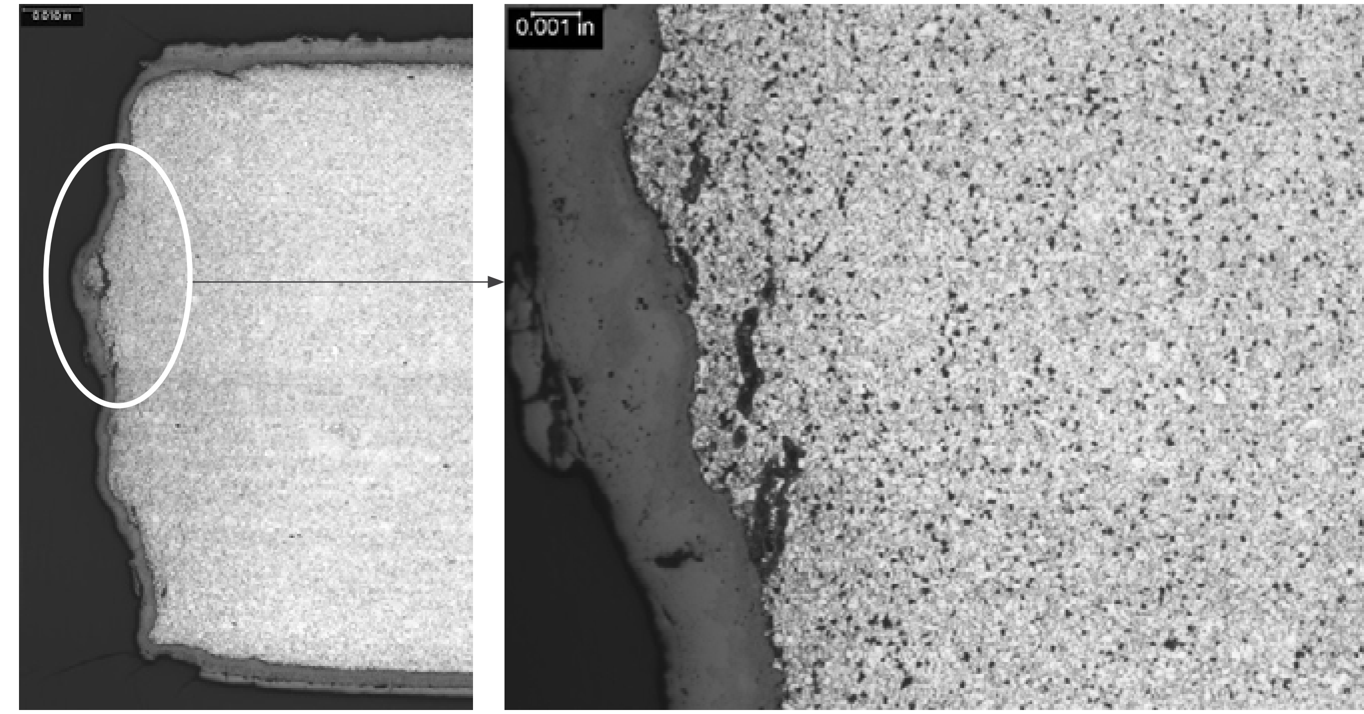

FIGURE 2. Crack surface of the tube to header weld crack, with a thick oxide layer and creep damage along its length.

TYPICAL LOCATIONS

- Superheater and reheater tubes where tube metal temperatures are in the creep regime
- Welded connections
- Bends
- Tube-to-header attachments

FEATURES

- Generally initiates on the OD surface
- Typically, single cracks
- Cracks are generally relatively straight, relatively wide, and oxide-filled or oxide-lined
- Creep voids and microfissures can surround the primary crack, but creep damage does not have to be present

ROOT CAUSES

Creep-fatigue is caused by the interaction of stresses, both cyclic and static, and elevated temperature exposure. Root causes can include excessive stresses/strains, excessive tube temperatures, and unit operation.

Excessive stresses/strains can result from the following, many of which are related to HRSG operation: constrained thermal expansion, pressure changes, fluid temperature changes, non-uniform temperatures, load transfer between hot and cold conditions, changes in external loads, transient temperature differences, steam or water hammer, forced vibration, flue gas flow problems, thermal transients due to condensate flashing into tube circuits, improper attemperation, and incorrect or inadequate drains.

Excessive tube temperatures can result from excessive temperature ramp rates, poor distribution of tube temperatures, poorly designed thickness transitions at header connections and supports, and poor material selection for tubing.

The number of service hours, number of stop/starts, and the characteristics of the stop/starts are unit operation influences that can affect creep-fatigue damage.

SIA MATERIALS SCIENCE CENTER (MSC) — FEATURED DAMAGE MECHANISM LIBRARY

Structural Integrity has an experienced group of materials specialists and a full-service metallurgical testing laboratory that can help with any situation involving material property characterization.

www.structint.com/metallurgical-laboratory-services

UPDATE: Encoded Phased Array Ultrasonic Examination Services for Cast Austenitic Stainless Steel (CASS) Piping Welds

in Pressurized Water Reactor (PWR) Coolant Systems

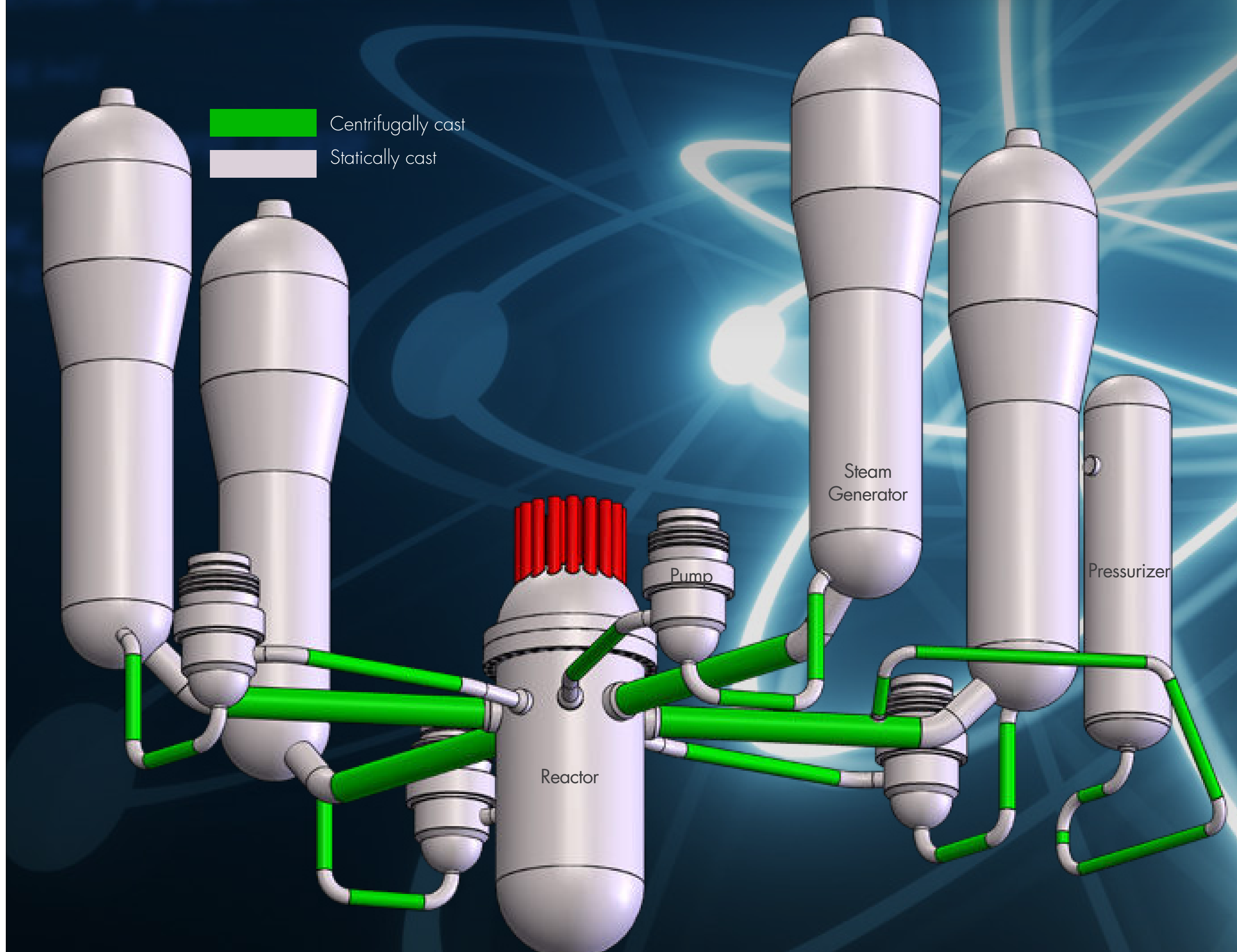

FIGURE 1. Locations of CASS piping components, both statically and centrifugally cast, in primary Reactor Coolant Systems of many U.S. PWR plants

JOHN HAYDEN
jhayden@structint.com

JASON VAN VELSOR
jvanvelsor@structint.com

The CASS piping welds in many nuclear plants present challenges for effective ultrasonic examinations. As a result, most CASS piping welds have not been subjected to a meaningful and effective volumetric examination since radiography was performed during plant construction. SI has developed and demonstrated a Code-compliant, procedure that enables in-service volumetric UT inspection in full compliance with the NRC's 10CFR50.55a.

Our initial article on this topic in News & Views, Volume 53[1] described the challenges imposed by cast austenitic stainless steel (CASS) materials and SI's corresponding development of our CASS UT Examination solution. At the time of the prior article's publication, SI was also conducting proof of concept examinations of numerous CASS piping specimens. This article provides details of both that performance demonstration and the results of those examinations.

TYPICAL CASS PIPING WELD LOCATIONS IN PWR REACTOR COOLANT SYSTEMS

Figure 1 illustrates the presence of CASS piping components, both statically and centrifugally cast, in the primary Reactor Coolant Systems of many U.S. PWR plants. Other PWR plant designs also contain CASS components, albeit in fewer locations and only in the form of short spool piece segments, usually for reactor coolant pumps and safety injection system safe ends.

REGULATORY BASIS FOR CASS EXAMINATION CAPABILITY

ASME Section XI Code Case N-824, which was approved by the NRC in 2019, provides specific direction and requirements for ultrasonic examination of welds joining CASS components. N-824 was incorporated into Section, XI, Appendix II, Supplement 2 in the 2015 Code edition. The NRC has stated (10CFR50.55a, 07/18/2017) that with use of the aforementioned N-824 methodology "Licensees will be able to take full credit for completion of the § 50.55a required in-service volumetric inspection of welds involving CASS components." SI's procedure development and demonstration were therefore based on these requirements.

ULTRASONIC TECHNIQUE PERFORMANCE DEMONSTRATION

Though not required by the ASME Code, SI conducted a performance demonstration of our CASS UT system at our facility in Huntersville, NC. Using CASS piping system specimens on loan from the EPRI NDE Center, SI successfully validated our ultrasonic examination system capabilities as follows.

Ultrasonic Procedure – SI's CASS ultrasonic examination procedure is fully compliant with ASME Section XI Code documents, and NRC-imposed technical approval conditions. The procedure has also been optimized with many insights gained from our laboratory experiences while examining EPRI-owned CASS piping specimens.

Ultrasonic Equipment - The ultrasonic system components required by Code have been designed and fabricated by SI or purchased, including the following:

- Ultrasonic instrumentation capable of functioning over the entire prescribed ranges of examination frequencies. The standard examination frequency range extends from low-frequency, 500 KHz operation for CASS pipe welds > 1.6" T_{nom} and 1.0 MHz for CASS pipe welds ≤ 1.6" T_{nom}
- Transducer arrays were employed to meet the physical requirements of frequency and aperture size capable of generating the Code-prescribed wave mode, examination angles, and focal properties.
- An assortment of wedge assemblies were designed and fabricated then mated with transducer arrays to provide effective sound field coupling to the CASS components being examined.

Data encoding options necessary to acquire ultrasonic data given the expected range of component access and surface conditions are available.

The encoding options include:

- A fully-automated scanning system capable of driving the relatively large and heavy 500KHz phased array probes. This system was used during our laboratory examinations of CASS piping specimens.
- A manually driven encoding system — a proven, field-worthy tool — which may be employed in locations where fully automated systems cannot be used because of access restrictions.

Examination Personnel - The challenges that exist with the examination of CASS piping welds warrant a comprehensive program of specialized, mandatory training for personnel involved with CASS examinations. This training includes descriptions of coarse grain structures, their effect on the ultrasonic field, the expected ultrasonic response characteristics of metallurgical and flaw reflectors, and the evaluation of CASS component surface conditions.

Additionally, SI's ultrasonic examination personnel are thoroughly trained and experienced in all elements of encoded phased array ultrasonic data acquisition and analysis in nuclear plants and hold multiple PDI qualifications in both manual and encoded phased array DM weld techniques.

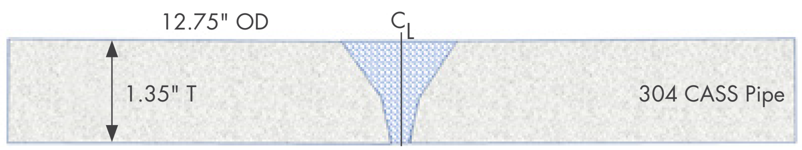

FIGURE 2. Schematic of 12.75" OD, 1.35" T_{nom} CASS specimens.

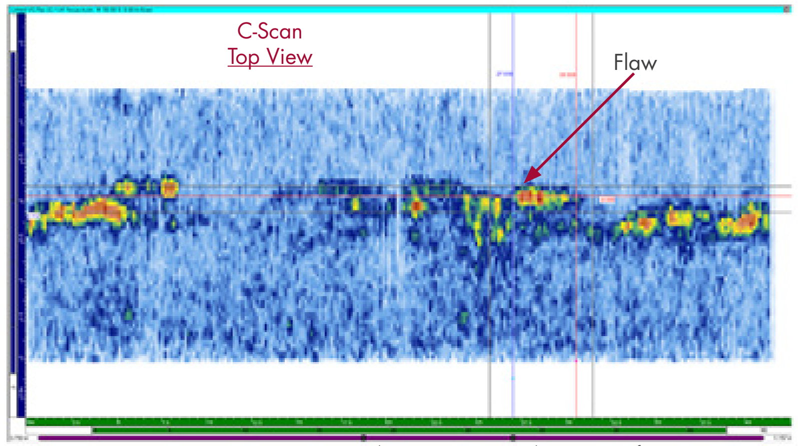

FIGURE 3. Representative ultrasonic C-Scan data image from 12.75" OD, 1.35" T_{nom} specimen.

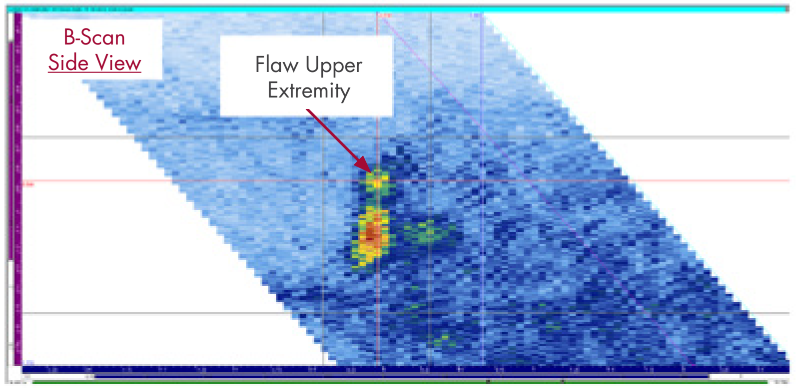

FIGURE 4. Representative ultrasonic B-Scan data image from 12.75" OD, 1.35" T_{nom} specimen.

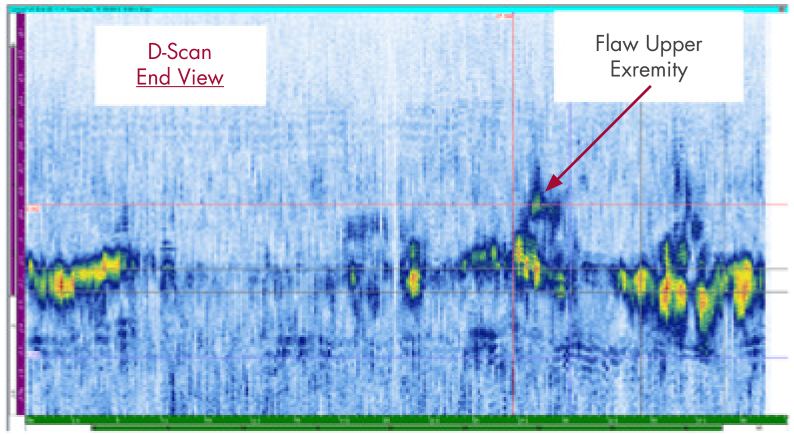

FIGURE 5. Representative ultrasonic D-Scan data image from 12.75" OD, 1.35" T_{nom} specimen.

EPRI CASS PIPING SPECIMENS

The EPRI CASS pipe specimens, their outside diameter (OD) and thickness dimensions, and butt weld configurations examined by SI are described below.

12.75" OD, 1.35" T_{nom} SPECIMENS

Three pipe-to-pipe specimens representative of piping found in pressurizer surge and safety injection applications were examined. Each of these specimens had the weld crown ground flush.

Figure 3, Figure 4, and Figure 5 present examples of ultrasonic data images of a flaw detected in a 12.75" OD pipe-to-pipe tapered specimen.

The C-Scan is a 2-D view of ultrasonic data displayed as a top (or plan) view of the specimen. The horizontal axis is along the pipe circumference, and the vertical axis is along the pipe axis or length.

The B-Scan is a 2-D view of ultrasonic data displayed as a side view of the specimen. The angular projection of the data is displayed along the examination angle. The horizontal axis is along the pipe axis, and the vertical axis is along the pipe thickness.

The D-Scan is a 2-D view of ultrasonic data displayed as an end view of the specimen. The horizontal axis represents the pipe circumference, and the vertical axis is along the pipe thickness.

28" OD, 2.0" T_{nom} SPECIMENS

Four pipe-to-pipe specimens representative of piping found in reactor coolant loops were examined. Each of these specimens had the weld crown intact and left in place.

Figure 7, Figure 8, and Figure 9 present examples of ultrasonic data images of a flaw detected in a 28" OD pipe-to-pipe tapered specimen.

The C-Scan is a 2-D view of ultrasonic data displayed as a top (or plan) view of the specimen. The horizontal axis is along the pipe circumference, and the vertical axis is along the pipe axis or length.

Note the ability of our UT data acquisition equipment and data analysis techniques to resolve, discriminate, and identify inside surface geometric conditions (weld root and pipe counterbore), along with detecting and sizing the flaw indication. Also, note the excellent signal-to-noise ratio achieved.

The B-Scan is a 2-D view of ultrasonic data displayed as a side view of the specimen. The angular projection of the data is displayed along the examination angle. The horizontal axis is along the pipe axis or length. The vertical axis is along the pipe thickness.

The D-Scan is a 2-D view of ultrasonic data displayed as an end view of the specimen. The horizontal axis is along the pipe circumference, and the vertical axis is along the pipe thickness.

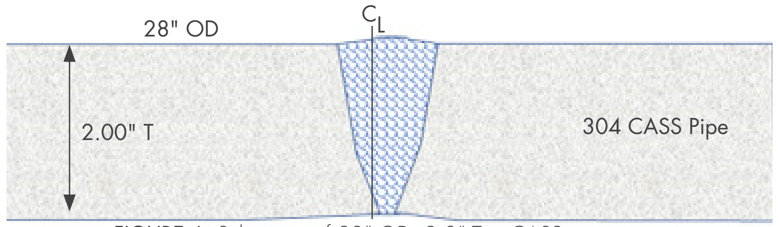

FIGURE 6. Schematic of 28" OD, 2.0" T_{nom} CASS specimens.

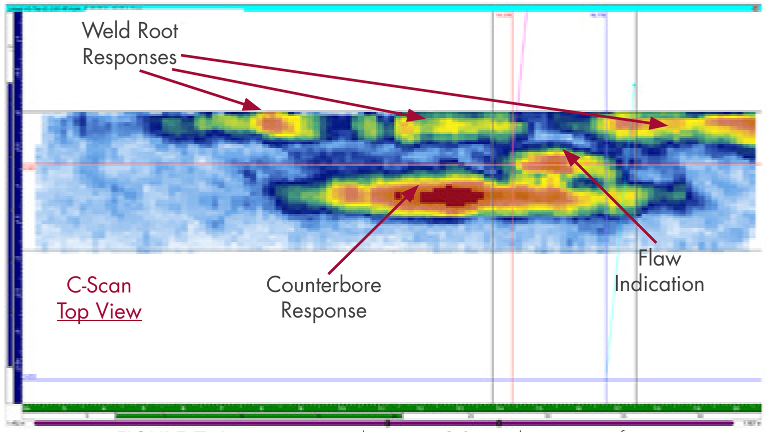

FIGURE 7. Representative ultrasonic C-Scan data image from 28" OD, 2.0" T_{nom} specimen.

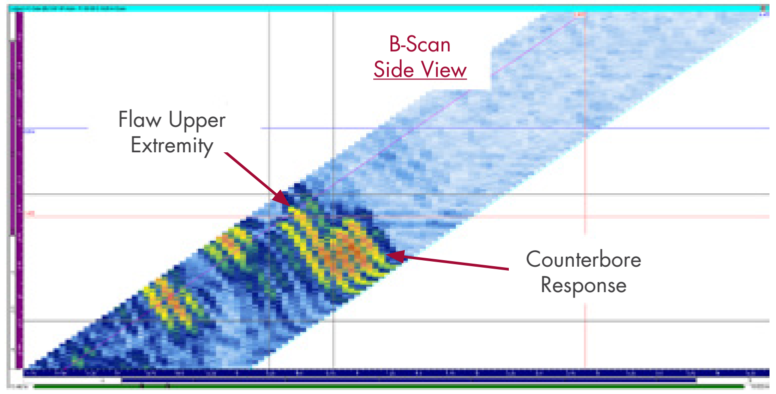

FIGURE 8. Representative ultrasonic B-Scan data image from 28" OD, 2.0" T_{nom} specimen.

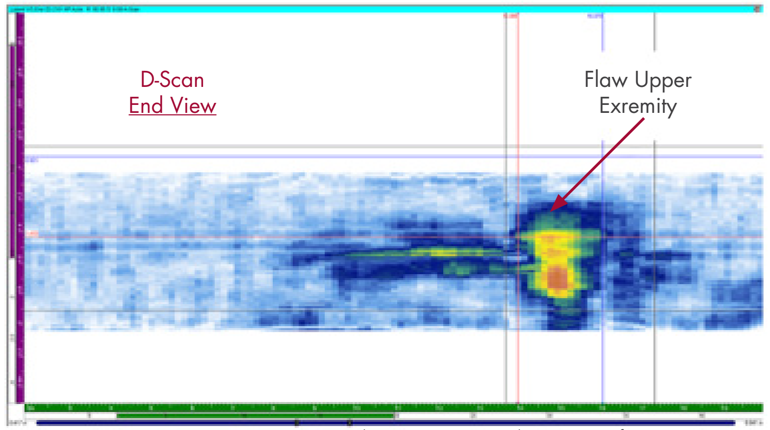

FIGURE 9. Representative ultrasonic D-Scan data image from 28" OD, 2.0" T_{nom} specimen.

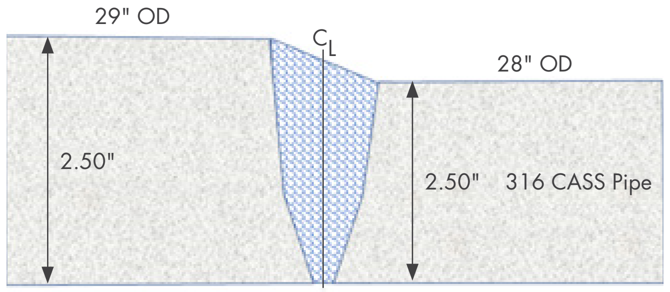

FIGURE 10. Schematic of 28" to 29" OD, 2.0" to 2.5" T_{nom} CASS specimens.

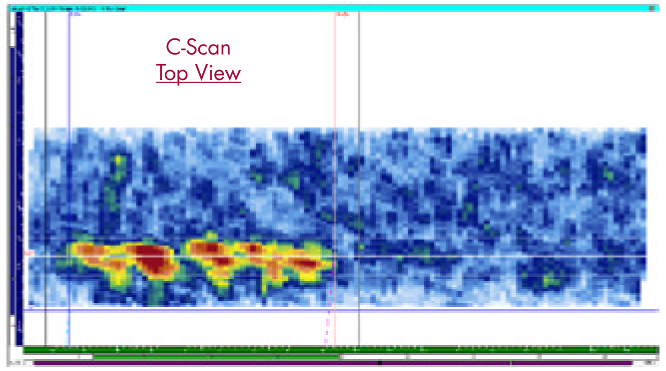

FIGURE 11. Representative ultrasonic C-Scan of a 28" to 29" OD, 2.0" to 2.5" T_{nom} pipe-to-pipe, with tapered weld surfaces.

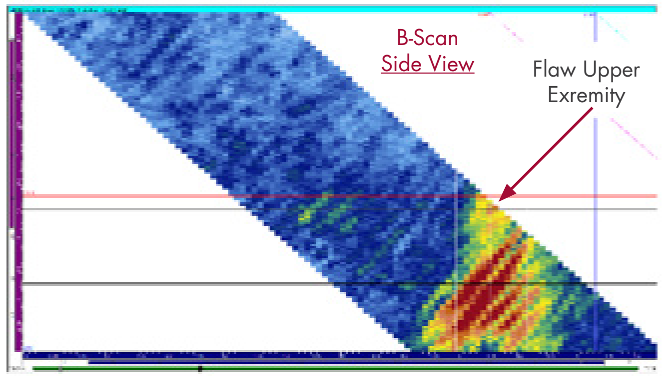

FIGURE 12. Representative ultrasonic B-Scan of a 28" to 29" OD, 2.0" to 2.5" T_{nom} pipe-to-pipe, with tapered weld surfaces.

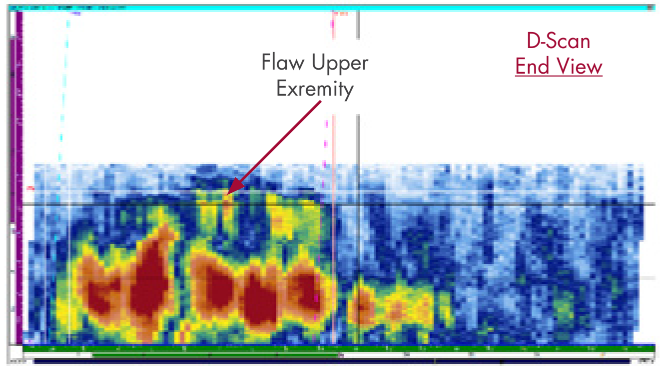

FIGURE 13. Representative ultrasonic D-Scan of a 28" to 29" OD, 2.0" to 2.5" T_{nom} pipe-to-pipe, with tapered weld surfaces.

28" TO 29" OD, 2.0" TO 2.5" T_{NOM} TAPERED WELD SPECIMENS

Four pipe-to-pipe specimens, with tapered weld surfaces representative of piping found in reactor coolant loops were examined.

Figures 11, 12, and 13 present examples of ultrasonic data images of a flaw detected in a 28" OD to 29" OD pipe-to-pipe tapered specimen.

The C-Scan is a 2-D view of ultrasonic data displayed as a top (or plan) view of the specimen. The horizontal axis is along the pipe circumference, and the vertical axis is along the pipe axis, or length.

The B-Scan is a 2-D view of ultrasonic data displayed as a side view of the specimen. The angular projection of the data is displayed along the examination angle. The horizontal axis is along the pipe axis or length. The vertical axis is along the pipe thickness.

The D-Scan is a 2-D view of ultrasonic data displayed as an end view of the specimen. The horizontal axis is along the pipe circumference, and the vertical axis is along the pipe thickness.

SUMMARY OF DATA ANALYSIS RESULTS

Documentation was provided for each EPRI specimen, which contains flaw location, length, and through-wall size to permit the comparison of UT data acquisition and analysis processes to actual flaw conditions.

All of the 23 circumferential flaws in the eleven EPRI specimens were detected. The ultrasonic examination and data analysis techniques achieved flaw location and length sizing RMS errors, which are within acceptance standards of the following ASME Section XI, Appendix VIII Qualification Supplements:

- Supplement 2, Qualification Requirements for Wrought Austenitic Stainless Steel Piping
- Supplement 10, Qualification Requirements for Dissimilar Metal Piping

Excellent signal-to-noise ratios were observed for all detected flaws.

For all flaws, the measured length achieved sizing RMS errors within the acceptance standards of the above Appendix VIII supplements.

For specimens with welds ground flush and for all specimens with sufficient access to interrogate the entire through-wall extent of flaws, SI's technique achieved through-wall sizing RMS errors within the acceptance standards of the above Appendix VIII supplements.
To be clear, the examination of the EPRI CASS specimens does not meet the rigor of Appendix VIII, Supplement 9 qualification because the industry's (PDI Program) for CASS piping welds is still in preparation. The comparison to Appendix VIII acceptance standards is provided solely as a means to describe the achieved flaw detection and sizing capabilities in CASS material in terms of already established PDI qualifications. Ongoing examination of additional CASS specimens will strengthen already existing ultrasonic examination capabilities and experience.

CONCLUSIONS

The CASS piping welds in many PWR plants provide numerous and complicated challenges to their effective ultrasonic examinations. Most, if not all, CASS RCS piping welds have not been subjected to a meaningful and effective volumetric examination since radiography was conducted during plant construction. SI's newly-demonstrated ultrasonic examination procedure for CASS delivers a demonstrated, Code-compliant, meaningful, and effective solution that provides full credit for completion of in-service volumetric inspection per § 50.55a.

References

[1.] News and Views, Volume 53, October 2023, "Encoded Phased Array Ultrasonic Examination Services for CASS Piping Welds In PWR Reactor Coolant Systems"

[2.] ASME Section XI Code Case N-824, "Ultrasonic Examination of Cast Austenitic Piping Welds from the Outside Surface"

[3.] ASME B&PV Code, Section XI, 2015 Edition and later editions

VOLUME 55 | **NEWS AND VIEWS**

Managing High Energy Piping: The Fundamental Approach, Integrating NDE and Engineering (Part-1)

ERIC JONES
ejones@structint.com

MATT DOWLING
mdowling@structint.com

High Energy Piping (HEP) programs help ensure safe and reliable operation of piping operating at elevated temperature and pressure at power and process facilities by identifying and inspecting critical locations and evaluating fitness for service. Seamless integration between Nondestructive Examinations (NDE) and engineering helps optimize inspection targets, minimize surprises, and accelerate serviceability evaluations. This maximizes value for owners/operators, enabling confident asset management and avoiding unnecessary downtime.

High Energy Piping (HEP) programs, also known as Covered Piping System (CPS) programs, are implemented to help ensure the safe and reliable operations of these critical systems at power and processing facilities. Effective programs rely on multiple technical disciplines, including the understanding of damage mechanisms, nondestructive examination, and engineering analysis. Critical locations are identified through a combination of operating experience, prediction of high stress locations through analytical assessments, and risk-based engineering. These locations are then examined using various NDE methods depending on the applicable damage mechanisms for the component and operating conditions. The results are then analyzed to determine their impact on both short- and long-term serviceability. The findings inform key decisions regarding continued operation, repair strategies, component replacement, and reinspection planning, following widely accepted industry practices aligned with ASME B31.1 and API 579.

This article, the first in a two-part series on optimizing HEP program value through engineering and inspection, focuses on how seamless **integration** of NDE and engineering drives effective decision-making. Part 2 will explore emerging technologies such as online monitoring, digital twins, and machine learning.

PROGRAM DEVELOPMENT

Effective HEP programs feature collaboration between engineering and NDE experts from the outset. Without this integration, inspections may miss critical damage, waste resources, or create unnecessary downtime. A well-designed program ensures that each inspection is strategically targeted and uses the appropriate methods to detect damage before it becomes a problem.

ALIGNMENT FROM THE START

A major step in HEP program development is defining inspection protocols—a process that hinges on accurate engineering insights. Engineering experts assess the design, material properties, operating history, consequence of failure, and stress conditions to evaluate potential damage mechanisms. This engineering assessment informs where and when service-related damage is likely to occur. NDE specialists then select the most effective inspection techniques for detecting the expected damage. Because no single method can fully characterize all potential issues, the right combination of techniques must be used:

- Surface methods like Wet Fluorescent Magnetic Particle (WFMT) or Liquid Penetrant (LP) for crack detection.
- Advanced ultrasonic techniques such as Linear Phased Array (LPA) or Time-of-Flight Diffraction (TOFD), and Focused Annular Phased Array (APA) to detect subsurface damage.

By working together early in program development, engineers and NDE specialists ensure that inspections are both targeted and efficient—focusing on high-risk areas while minimizing unnecessary examinations.

FIELD INSPECTIONS

Field inspections represent the hands-on element of HEP programs, ensuring that damage mechanisms are properly identified and evaluated. This process consists of four key phases—Detection, Quantification, Classification, and Documentation—each requiring engineering involvement to ensure accuracy and to make results actionable.

DETECTION

Detection is the foundation of any field inspection. Success depends on selecting the correct NDE technique, as informed by engineering expertise, and the technician's expertise in flaw detection. For example, WFMT is ideal for surface-breaking flaws, while LPA excels at identifying subsurface or ID-connected cracks. Without proper alignment between engineering predictions and NDE execution, critical flaws may go undetected.

QUANTIFICATION

Quantification ensures that flaw characteristics—such as location, size, and orientation—are precisely recorded. This information is critical for determining the severity of flaws and supporting accurate fitness-for-service (FFS) evaluations. Example characteristics include:

- Is the indication located on the OD, ID, or mid-wall (subsurface)?
- Is the indication located in the base metal, heat-affected zone, or weld metal?
- What is the profile of the indication (axial or circumferential length, through-wall extent, etc.)

Even minor quantification errors can lead to unnecessary repairs or missed critical damage. Engineering oversight helps ensure precision and reduces the risk of overestimating or underestimating flaw severity.

CLASSIFICATION

Flaw classification is the most complex phase of field inspections, requiring advanced NDE knowledge, engineering expertise, and in many cases, a metallurgical assessment of a core or boat sample. The goal is to determine whether an indication is fabrication related (e.g., slag, lack of fusion, etc.) or service-related (e.g., creep, fatigue, etc.). This distinction is absolutely critical – two flaws of the same size can have vastly different consequences depending on their origin.

To refine classification, additional or augmented methods may be used to confirm findings. For example:

- Surface replication allows metallurgical analysis of a microstructure at the tip of a crack if it is at the outer surface, confirming whether the damage is creep-related or due to another mechanism.
- In cases where flaws are evaluated over time with two or more inspections, ultrasonic testing is used to quantify subsurface flaws, helping to determine whether a crack is propagating and at what rate.
- In cases of subsurface flaws, metallurgical assessment of a core or boat sample is often required to definitively classify a flaw origin.

Accurate classification of complex flaws requires an understanding of many factors, including probe selection, technique limitations, data processing/imaging, metallurgy, and damage morphology. Often this is best accomplished with the NDE technician and engineer sitting side-by-side.

Once a flaw is confirmed as service-related, engineering unput is often required to ascribe the specific degradation mechanism. For example, creep damage occurs due to long-term exposure to high-temperature stress, whereas fatigue cracking results from cyclic loading (e.g., starts/stops). While both indications may appear similar, their progression rates and repair priorities differ significantly.

DOCUMENTATION

Documentation is the final phase—and possibly the most critical. Clear, high-quality records ensure that inspection findings are properly communicated to guide future reinspection intervals and be used to adjust program assumptions as necessary. Poor documentation can lead to lost historical data, making it difficult to track flaw progression over time. Engineering involvement helps ensure that reports capture not only inspection results but also actionable recommendations for repair, continued operation with reinspection, or further evaluation.

WHAT CAN GO WRONG WHEN MISALIGNED?

When engineering and NDE are not fully aligned during program development, it can lead to:

Missed Damage Due to Incorrect NDE Techniques/Instructions

- If engineering input is incorrect or missing, inspections may focus on the wrong damage mechanisms, leading to undetected flaws that could worsen over time.
- Example: For instance, a recent industry-wide issue has been found in Tee fittings that are insufficiently reinforced to handle long-term pressure stress and have failed in the crotch areas. Without an understanding of the damage mechanism including locations in which it manifests, a technician would typically only inspect the associated girth welds rather than doing a complete evaluation of the tee crotch area including the base metal to detect subsurface cracking between the girth welds.

Unnecessary Inspections That Waste Time and Resources

- A lack of engineering guidance can result in the inspection of locations which are less consequential or likely to fail. An optimized scope will provide the best value with respect to inspection budget leading to a safer operating environment.
- Example: SI has been involved with numerous cases where "random" inspection programs without the aid of stress analysis and subsequent life calculations were either not aggresive enough or not targeted to the locations with highest likelihood of failure. While welds throughout the systems were being inspected, they were not the welds with highest likelihood of failure or associated with known industry issues – as found through analysis after the incidents occured, unfortunately.

WHAT CAN GO WRONG IN THE INSPECTION PROCESS?

There are several critical steps to the inspection process. Mishaps in any one of the steps can lead to serious consequences.

Missed Flaws Due to Inconsistent NDE Execution

- If NDE instructions are vague, misinterpreted, or poorly executed, critical flaws may go undetected.

Inaccurate Flaw Size Leading to Incorrect Engineering Assessments

- Poor quantification can lead to dangerously unconservative Fitness-for-Service determinations or overly-conservative and expensive repairs/replacements.

Incorrect Classification Misses Critical Service-Related Damage or Causes Unnecessary Repairs

- Misidentifying a service-related as fabrication-related dlaw can lead to unmonitored damage progression and failure.

Poor Documentation Leads to Loss of Inspection History

- Lack of detailed records makes it difficult to track flaw growth over time, leading to incorrect reinspection intervals or misjudged repair priorities.

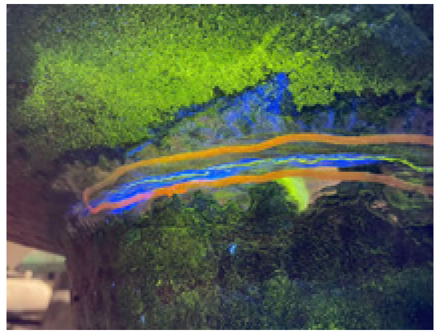

FIGURE 1. Typical WFMT Indication

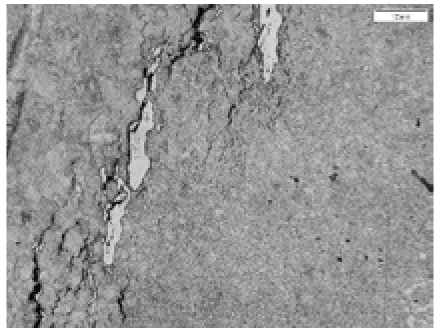

FIGURE 2. Typical replication at the tip of a WFMT indication showing creep damage

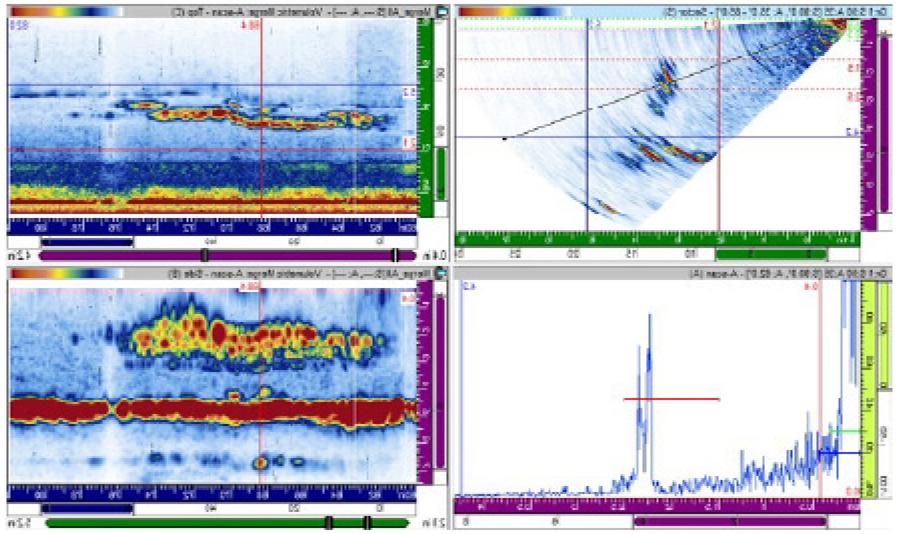

FIGURE 3. LPA Image of mid-wall creep-like damage

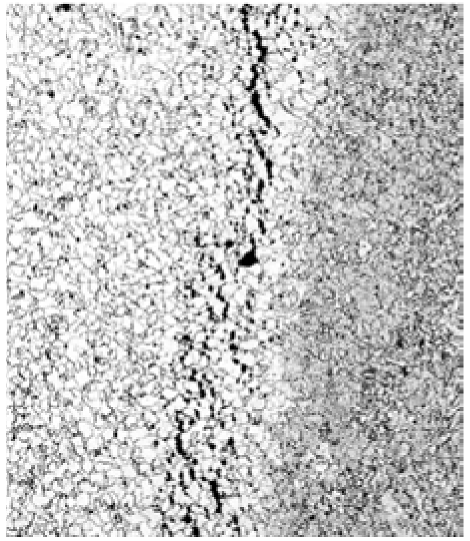

FIGURE 4. Photomicrograph of mid-wall creep damage in the heat affected zone

ENGINEERING SERVICEABILITY ASSESSMENTS

When inspections identify flaws, degradation, or unexpected damage, the next step is to determine whether the affected component can continue operating safely or requires repair or replacement. This evaluation is driven by engineering serviceability assessments, where advanced analysis techniques are used to quantify risk, predict failure potential, and guide operational decision-making.

Fitness-for-service (FFS) evaluations, performed in accordance with API 579 / ASME FFS-1, play a critical role in this process. These assessments involve:

- **Stress analysis**: evaluating operating stresses, thermal gradients, and residual stress effects.
- **Fracture mechanics**: determining whether detected cracks are stable or at risk of propagation, and at what rate.
- **Creep life assessments**: predicting localized degradation in materials exposed to high temperatures.
- **Metallurgical analysis**: confirming damage mechanisms and material embrittlement.

Many of these assessments require detailed finite element analysis (FEA) to model stress distributions and crack growth across a range of operating conditions. SI engineers specialize in developing detailed models that accurately characterize field conditions and provide precise inputs to remaining life calculations. Their practical experience with field configurations and inspection methodologies helps streamline analyses, enabling faster development of actionable conclusions for plant operators.

CONTINUOUS PROGRAM OPTIMIZATION

A well-designed HEP program is not static—it must evolve based on inspection findings, operational conditions, and emerging degradation trends. Continuous collaboration between engineering and NDE teams ensures that inspection strategies remain data-driven, risk-informed, and aligned with long-term reliability goals.

Inspection results and engineering assessments must feed back into the HEP program to refine reinspection intervals, update risk models, and optimize NDE methodologies. Without a structured approach to cataloging and analyzing inspection data, valuable insights can be lost—leading to inefficient inspections or missed opportunities for proactive maintenance. SI's PlantTrack™ software provides a centralized platform for storing, visualizing, and analyzing HEP inspection data—ensuring that past findings directly inform future asset management decisions. By leveraging PlantTrack™, operator staff and SI's engineering and NDE teams can maintain seamless integration for optimized HEP asset management.

Advancements in predictive analytics and real-time monitoring are set to fundamentally transform HEP program management, shifting from a reactive approach to a truly predictive asset management strategy. As these technologies continue to evolve, their integration with traditional inspection and engineering methodologies will be key to maximizing plant reliability and extending the life of critical piping systems. In the forthcoming Part-2 of this article, we will explore SI's latest advancements in these areas, including digital twins, machine learning applications, and online condition monitoring.

BRINGING IT ALL TOGETHER: A REAL-WORD EXAMPLE OF INTEGRATED HEP PROGRAM SUCCESS

When a 1,300 MW conventional boiler plant discovered a small failure in a longitudinal seam weld on its Reheat Steam line, the operator was concerned about the potential for more widespread damage. SI was engaged to perform a comprehensive inspection and engineering assessment to evaluate system integrity and prevent future failures.
The initial directive from the operator was to inspect 2/3 of the existing system. SI's engineering and NDE teams collaborated to develop a risk-based inspection plan, prioritizing high-risk locations to maximize impact. This risk-informed strategy was intended to maximize efficiency while ensuring no critical damage was overlooked. The resulting original work scope included:

- 1,069 feet of longitudinal seam welds.
- 115 girth welds.

SI deployed a multidisciplinary team, ensuring real-time collaboration between engineers and NDE specialists. The onsite inspections included:

- WFMT on all girth welds, longitudinal seam welds, and attachments, for detection of surface flaws.
- Fully encoded LPA UT (girth welds) and TOFD and Focused APA (seam welds) for detection of subsurface flaws.
- Metallurgical replications to confirm damage mechanisms.

- Dimensional measurements and laser profilometry for accurate component characterization.

The initial inspection findings included:

- Cracking in five additional seam welds.
- Welds fabricated with improper materials.

Based on these findings, SI recommended expanding the inspection scope and making real-time adjustments to the plan. As a result, the final inspection tally included:

- 1,375 feet of longitudinal seam welds (191 total).
- 160 girth welds.
- 15 saddle welds and 157 attachment welds.

The entire field inspection effort was completed in less than one month. In parallel, SI's engineering team provided real-time fitness-for-service (FFS) evaluations, ensuring inspection data directly informed run-repair-replace-reinspect decisions. Destructive testing on extracted weld samples further validated material conditions and long-term risks.

The results of the effort provided the operator with a roadmap for future inspections, ensuring:

- Optimized reinspection intervals based on actual degradation rates.
- Risk-based monitoring and maintenance strategies to prevent future failures while aligning with operational goals.

By aligning engineering expertise with advanced NDE methodologies, the plant operator identified and resolved immediate safety concerns while implementing a proactive approach to future HEP asset management.

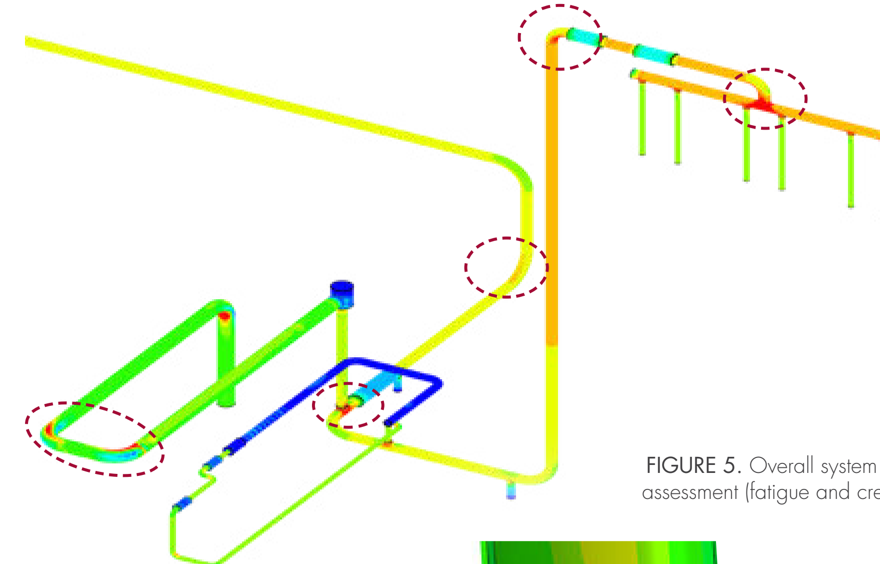

FIGURE 5. Overall system risk assessment (fatigue and creep)

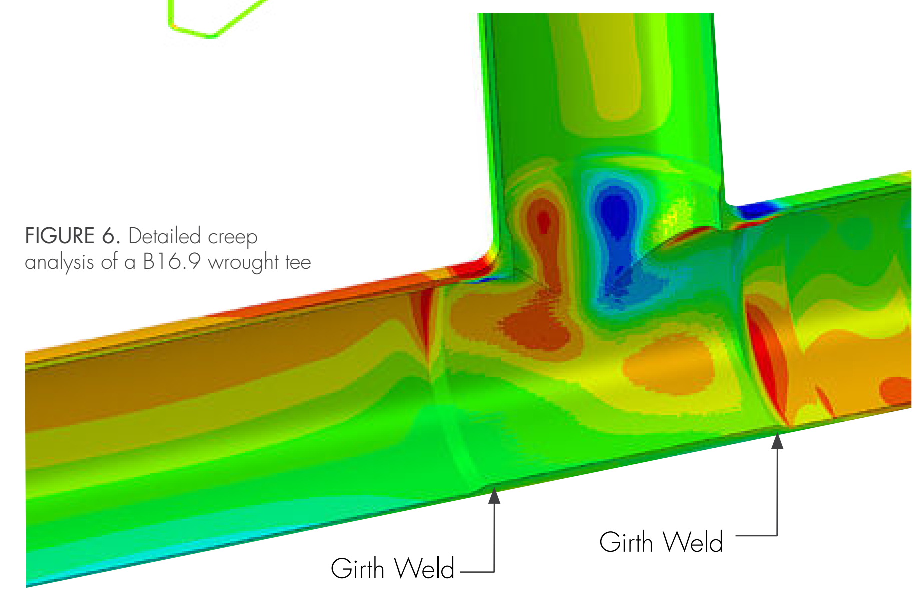

FIGURE 6. Detailed creep analysis of a B16.9 wrought tee

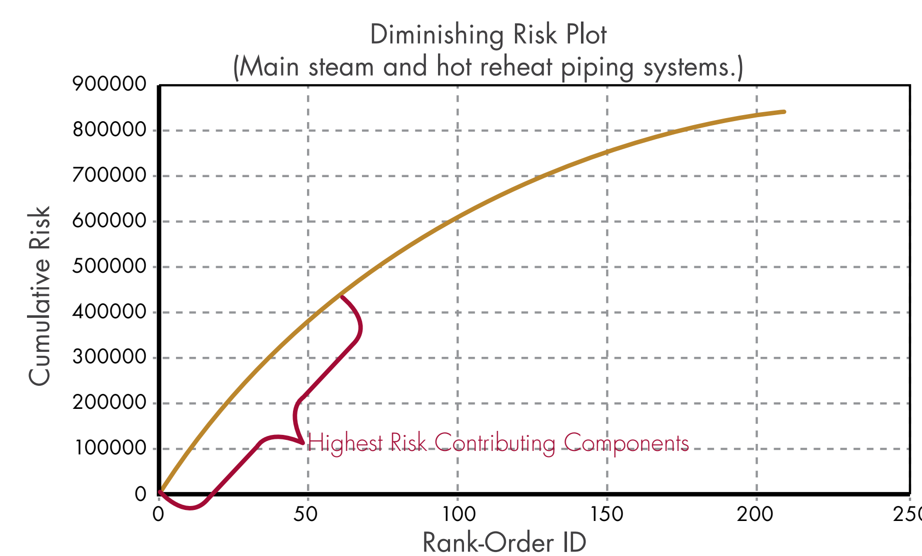

FIGURE 7. Comparison of relative risk vs. number of inspections

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