

News & Views



**Siemens 13.9m² Disk Bore Keyway
Nondestructive Examination
Re-development**

SIA's Holistic Approach to Rotor Life Assessments

CEO Message

In last year's message, I reflected on the pace of change at SI Solutions — the MidOcean partnership, our six business units, and the momentum we had built entering 2025. What I could not have fully anticipated was how quickly that momentum would continue to build. This past year has reinforced something I have believed since we began constructing this platform: when you invest in the right capabilities and the right people, the results follow. Today, SI Solutions is a fully integrated company operating across eight business units, with meaningfully deepened capabilities in every market we serve.

GROWING THE PLATFORM

Since our last issue, SI Solutions has welcomed three new additions to the platform. In June 2025, we brought on Flesch Engineering, a Houston-based multidisciplinary firm specializing in mechanical, structural, civil, I&E, process, and rail engineering, with strong construction administration and program management capabilities that complement our existing energy sector offerings.

That September, we acquired Integrity Specialists, expanding our advanced non-destructive examination and inspection capabilities for the natural gas pipeline industry. The integration

significantly increases the scale and depth of what we can offer the midstream market, building on NDE expertise that has long been a core strength of SI Solutions.

Most recently, in February 2026, we added Radiological Solutions Inc. (RSI) to our nuclear business. RSI brings specialized expertise in nuclear chemistry, equipment design, radiation management, and environmental services — extending SIA's turnkey capabilities to the global nuclear power industry at a time when demand for nuclear operational support continues to grow.

INVESTING IN OUR TEAM

Growth at SI Solutions is not measured in acquisitions alone. Over the past year, we have strengthened the team from within — moving talented people into roles where they can have greater impact, creating new positions to better serve the market, and making strategic hires that deepen our technical capabilities across the platform. In total, we have added approximately 50 new engineering and technical staff across our businesses this past year, expanding the expertise available to our clients for everyday project support, peak period demands, and emergent situations alike. Every decision reflects the same principle: building an organization that delivers on its commitments.

MARK W. MARANO
President and CEO

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OUR IDENTITY, SHARPENED

Underlying all of this growth is a clearer sense of who we are and how we present ourselves to the industry. If you are reading this in print, you are holding something that reflects more than a design refresh. The cover of this issue is a statement — one that puts a sharper face on an identity SI Solutions has been building since day one. From the beginning, our intent has been to build an integrated platform: not a holding company, not a collection of capable firms operating independently, but a unified team capable of solving complex problems across the full range of critical infrastructure. We identify the vulnerability, and we resolve it faster. What is new is how clearly we are now able to say it: SI Solutions — Integrated Critical Infrastructure Specialists.

REAL PROBLEMS. CRITICAL CAPABILITIES. ESSENTIAL OUTCOMES.

Drawing on the industry's deepest bench of technical experts, we exist to bridge the resource gap, maximize uptime, navigate unprecedented demand, and keep essential infrastructure performing. Our clients benefit from a single partner that can design, test, monitor, and validate critical infrastructure systems — without the coordination burden and coverage gaps that come with managing

multiple niche providers. That is what this platform was built to do.

We are proud of what we have built, and we are excited to bring its full capability to bear for the clients who depend on us.

IN THIS ISSUE

The articles in this edition reflect the breadth of what the SI Solutions platform is built to deliver — and in many cases, the depth that sets us apart.

NUCLEAR

Nuclear continues to be a defining area of strength. Four articles in this issue speak directly to the demands facing nuclear operators today. Our redeveloped inspection protocol for Siemens low-pressure turbine rotor disk bores achieves 100 percent coverage across all six disks without rotor destacking — a capability with real consequences for outage planning and rotor life assessment. For plants pursuing subsequent license renewal, we address two distinct aging management challenges: evaluating and upgrading underperforming cathodic protection systems for buried piping and establishing a technically defensible basis for substituting external wall thickness measurements for internal visual inspections of coatings and linings — reducing radiation exposure without compromising compliance. And as advanced reactor designs move toward licensing, our fracture mechanics team outlines how Leak-Before-Break and flaw tolerance assessments provide the technical foundation for confirming structural reliability under the ASME RIM framework.

ENERGY & INFRASTRUCTURE RELIABILITY

Reliability and resilience across the broader energy and infrastructure landscape is equally well represented. One article details a damped support solution for small-bore piping vibration that reduced equivalent stress at critical

weld locations by more than 90 percent — a meaningful development for any plant managing fatigue-driven failure risk. Our seismic team contributes two pieces: a practical framework for qualifying battery energy storage systems in seismically active regions, and a look at two Pacific Northwest transportation projects where friction-pendulum isolation technology was applied — including a world-first track bridge installation on Seattle's I-90 floating bridge.

FAILURE ANALYSIS & DAMAGE MECHANISMS

Understanding how and why components fail is foundational to everything we do. This issue includes practical guidance on evidence preservation and documentation practices that determine whether a failure analysis yields defensible findings — a topic relevant to any engineering team that manages high-consequence assets. Complementing that, our materials lab examines stress corrosion cracking in boiler and HRSG tubes: a damage mechanism that often spreads well beyond the first visible failure.

PIPELINE INTEGRITY

Our pipeline integrity capabilities — strengthened this past year with the addition of Integrity Specialists — are on display in an article describing a first-of-its-kind engineering critical assessment methodology for lap-welded pipe. Working with PG&E, our team combined fracture mechanics and customized phased array ultrasonics to evaluate legacy assets that conventional inspection techniques struggle to adequately characterize.

PROCESS INDUSTRIES

The process industries work in this issue reflects the integrated engineering capability that our C2C Technical Services and Flesch Engineering teams bring to the platform. One article follows a Houston chemical plant from FEED through construction-ready

deliverables for a first-of-its-kind process technology installation — managing 3D laser scanning, controls design, and structural modifications while the facility remained in operation. A second draws on several recent Gulf Coast recovery projects to illustrate how C2C combines rapid field mobilization with concurrent engineering to restore electrical and instrumentation infrastructure after petrochemical facility fires.

DIGITAL INNOVATION

Finally, two articles address the intersection of engineering and emerging technology — an area of growing importance across every industry we serve. Our SC Solutions team examines the application of physics-based digital twin technology to semiconductor thermal processing equipment, using Kalman filter banks and disturbance observers to detect faults in real time. And a framework article tackles one of the more practical challenges in asset management: applying AI responsibly to weld integrity programs — using it to extract and structure decades of legacy inspection data while preserving engineering accountability for every safety-critical decision.

From cover to cover, the common thread is the one that has always defined SI Solutions: technical depth in service of operational outcomes. I hope you find this issue valuable, and welcome the opportunity to discuss how our capabilities can support your work as integrated critical infrastructure specialists.

Mark



In this Issue

2 **CEO Message**

6 **Lining and Coatings Degradation Assessments in Supporting Nuclear Power Plant License Renewal Applications**

Internal inspections of piping coatings and linings are required under nuclear license renewal, but depending on system location, they can increase radiation exposure, challenge dose goals, and take safety systems out of service. This article describes SIA's analytical approach to establishing a technically defensible basis for substituting external wall thickness measurements for internal visual inspections, in compliance with the XI.M42 aging management program requirements of NUREG-2191.

8 **Reducing Vibration-Induced Stress in Small-Bore Piping Using Damped Support Systems**

Socket weld failures from vibration-induced fatigue are a persistent challenge in operating plants. This article presents a cone shell support with polymer infill that combines structural stiffening with added damping. Developed through analytical screening and experimental validation with EPRI, the solution reduced vibration by up to 46 percent and cut equivalent stress at critical weld locations by 94 to 95 percent. The design is suited for retrofit applications.

12 **Seismic Preparedness for Battery Energy Storage Systems**

As battery energy storage systems (BESS) expand into seismically active regions, qualification requirements are growing more complex and vary by facility type, site seismicity, and applicable code. This article walks through the performance levels, qualification methods, and key standards governing BESS seismic certification, including IEEE 693, ASCE 7, and California-specific requirements. SIA and its subsidiary TRU Compliance offer turn-key qualification support.

15 **Important Considerations for Successful Failure Analyses**

When a component fails, how the failure event is documented and the evidence preserved can be as consequential as the laboratory analysis that follows. This article outlines practical guidance for engineers and plant personnel — from photographing failed components and collecting exemplar parts, to proper sample handling in the lab — to ensure a failure analysis yields defensible findings.

18 **Innovative Seismic Isolation Bearings Strengthen Critical Transportation Infrastructure Across the Pacific Northwest**

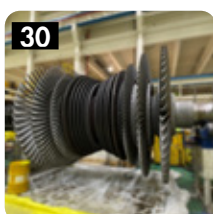
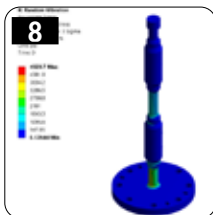
Seismic isolation bearings are well established for protecting bridges from earthquake forces. This article examines two Pacific Northwest transportation projects where SIA applied friction-pendulum isolation technology: a seismic retrofit and widening of the Abernethy Bridge on I-205 near Portland designed to remain operational after a major earthquake, and a world-first track bridge system on Seattle's I-90 floating bridge, enabling light rail to cross a structure that moves continuously in multiple directions.

24 **Digital Twin for Semiconductor Process Equipment – Potential and Challenges**

Semiconductor wafer fabrication demands temperature uniformity tolerances measured in fractions of a degree. This article examines how SC Solutions is applying physics-based digital twin technology to rapid thermal processing equipment, using Kalman filter banks and disturbance observers to detect sensor and actuator faults in real time, enabling predictive maintenance and reducing unscheduled downtime in chip fabrication facilities.

30 **Siemens 13.9m² Disk Bore Keyway Nondestructive Examination Re-development**

Shrunk-on disk bore and keyway regions on Siemens 13.9m² low-pressure turbine rotors are vulnerable to stress corrosion cracking but historically difficult to inspect with full coverage. SIA redeveloped its automated phased array ultrasonic testing protocol using advanced CAD modeling and simulation to optimize probe placement and achieve 100 percent disk bore coverage across all six disks without rotor de-stacking. The validated protocol, completed within a predictable five-day outage, supports defensible rotor life assessments for nuclear utilities.



35 **Leak-Before-Break and Flaw Tolerance for Advanced Reactors Under RIM Strategy**

As small modular reactors and other advanced nuclear concepts move toward licensing and deployment, demonstrating structural reliability under the ASME BPVC Section XI, Division 2 Reliability and Integrity Management framework is increasingly critical. This article outlines how flaw tolerance analysis and Leak-Before-Break assessments, supported by SIA's fracture mechanics tools and active participation in the ASME Code, provide the technical foundation for confirming component reliability.

40 **From FEED to IFC: Delivering New-to-Site Process Technology on an Accelerated Schedule**

Introducing a process technology that has never been used at a facility demands more than standard engineering execution — it requires careful integration of new and existing equipment, multidisciplinary coordination, and the ability to maintain momentum under schedule pressure. This article describes how C2C Technical Services guided a Houston chemical plant from FEED through construction-ready deliverables, incorporating 3D laser scanning, controls design, and new structural elements while the facility remained in operation.

42 **Modernization of a Legacy Cathodic Protection System for Subsequent License Renewal**

Nuclear plants pursuing subsequent license renewal must demonstrate that buried piping and tanks will remain protected through an extended operating period. This article details how SIA evaluated and upgraded the underperforming CP system at Xcel Energy's Monticello Nuclear Generating Plant, combining historical data review, field testing, and a hybrid impressed current design to raise protection coverage from roughly 50 percent to more than 85 percent without full system replacement.

48 **Materials Lab Featured Damage Mechanism: Stress Corrosion Cracking in Boiler and HRSG Tubes**

Stress corrosion cracking is among the more insidious damage mechanisms in boiler and heat recovery steam generator tubing — by the time the first leak appears, many tubes in the same circuit have often already sustained damage. This article examines the conditions required for SCC to develop, typical failure locations, and characteristic features that aid identification.

50 **Engineering Critical Assessment of Lap Welds**

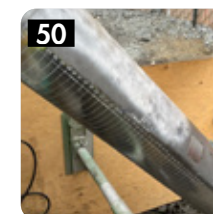
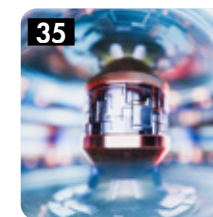
Lap-welded pipe, primarily manufactured in the 1920s and 1930s, carries inherent manufacturing defects that conventional inspection techniques struggle to adequately assess. Working with PG&E, SIA developed a first-of-its-kind ECA methodology that combines fracture mechanics analysis and a customized phased array ultrasonic inspection protocol to evaluate these legacy assets under 49 CFR Part 192, providing a defensible alternative to full pipe replacement or hydrostatic retesting.

53 **Using AI to Unlock Asset Integrity Data — Without Sacrificing Safety, Accuracy, or Future Readiness**

Decades of inspection records, scattered across inconsistent formats, create serious data management challenges for asset-intensive facilities. This article presents a framework for applying AI responsibly across asset integrity programs, using it to extract and structure legacy inspection data while simultaneously capturing new data digitally, creating a validated single source of truth. Engineering accountability is preserved throughout: AI surfaces and organizes data, but qualified engineers retain responsibility for every safety-critical decision.

56 **Rapid Recovery: Rebuilding Electrical & Instrumentation Systems After Petrochemical Refinery Fires**

Fires in petrochemical facilities damage far more than what is immediately visible. This article draws on several recent Gulf Coast recovery projects to illustrate how C2C Technical Services combines rapid field mobilization with concurrent engineering support to develop replacement designs, revise documentation, and execute construction to restore electrical and instrumentation infrastructure for safe operation of critical process units.



Lining and Coatings Degradation Assessments in Supporting Nuclear Power Plant Licensing Renewal Applications



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INTRODUCTION

In nuclear power plants, internal linings and coatings help ensure the integrity of piping systems and maintain a barrier against corrosive environments. As part of the license renewal process, plants are required to perform internal inspections of coatings and linings to ensure that degradation does not occur.

Degradation of these coatings and linings can expose susceptible piping materials to corrosive environments, accelerating corrosion rates. Additionally, the degradation and release of internal coatings and linings as debris can result in downstream impacts on systems, such as reduced system pressure, flow blockages, and heat exchanger fouling.

Structural Integrity has developed a robust analytical approach that provides the necessary justification to alleviate the need for internal visual inspections, thereby reducing radiation exposure and minimizing system out-of-service time.

As part of the subsequent license renewal process described in the U.S. Nuclear Regulatory Commission's

NUREG-2191, nuclear power plants are required to visually inspect all internal linings and coatings for those systems that fall within the scope of license renewal. Depending on the system and location of the internal coatings/linings, these inspections can challenge personnel dose exposure goals and safety system out-of-service times and can also prove to be costly and time-intensive.

As an alternative to performing internal inspection of coatings and linings,

plants may have the option to perform external wall thickness measurements. This alternative can be performed more quickly, while eliminating the need to remove safety systems from service.

In accordance with the guidance in aging management program XI.M42 of NUREG-2191, to perform external thickness measurements in lieu of internal visual inspections, the conditions shown in Figure 1 below must be met:

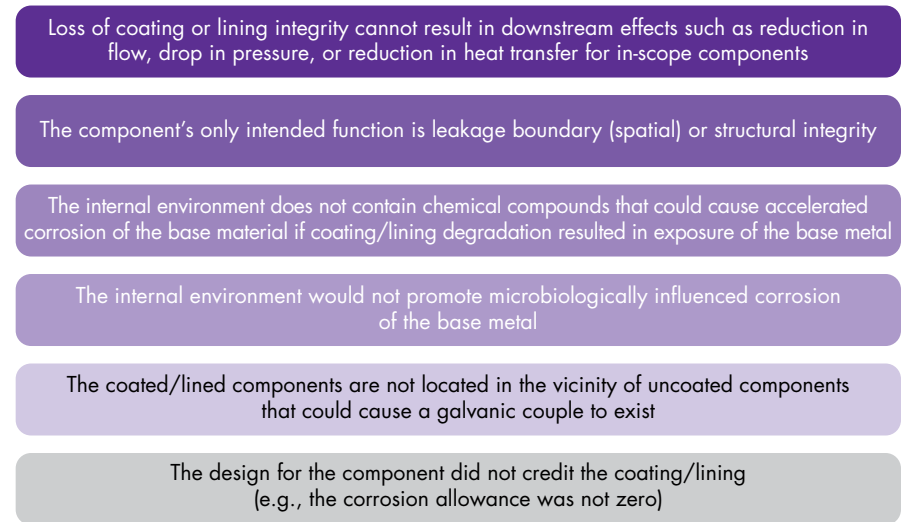


FIGURE 1. Requirements to perform UT in lieu of internal coating inspections

Structural Integrity Associates' comprehensive approach for evaluating in-scope coatings and linings addresses each of the requirements stipulated in the XI.M42 aging management program (AMP).

DETERMINATION OF COATING LINING FAILURE MECHANISMS

Internal coatings and linings can be found in both water- and oil-based systems, including nuclear safety-related cooling water and diesel fuel oil systems. In many cases, these linings were supplied with the original piping during plant construction or were applied at the beginning of commercial operation. Often, these coatings and linings have reached or exceeded their original qualified life.

SIA personnel have experience evaluating a range of internal coatings and linings, from cured epoxies to extruded polypropylene-lined piping. By understanding the nature of the installed coating/lining, plausible failure modes can be determined.

DESIGN CONSIDERATIONS FOR EVALUATING LINING FAILURES

EVALUATION OF SYSTEM IMPACT

To justify performing external thickness measurements in lieu of internal visual inspections, it must be determined that a release of the coating or lining does not impact downstream system functions.

SIA personnel have a strong technical understanding of the licensing basis

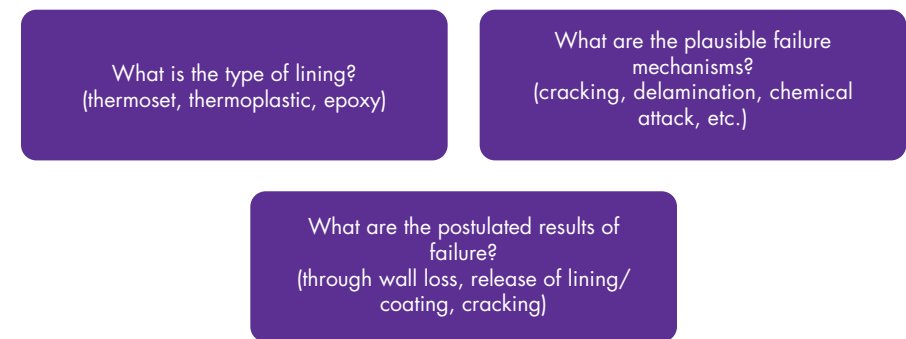


FIGURE 2. Design Considerations when evaluating coatings and lining failures

functions for the various systems within the scope of license renewal. By understanding the system design functions, their performance margin, and the nature of the release of failed coatings/linings, the impact on downstream components can be assessed. When assessing the potential impact of coating/lining failures, a worst-case failure of the lining is evaluated.

ASSESSMENT OF SYSTEM CORROSION SUSCEPTIBILITY

To eliminate the need for internal visual inspections of coatings and linings, it must be determined that the underlying piping is not susceptible to accelerated corrosion rates due to chemical attack, microbiologically influenced corrosion, and/or galvanic corrosion. By providing a holistic evaluation that assesses the chemical environment, material susceptibility, and design requirements, SIA can provide a comprehensive evaluation of the piping corrosion mechanisms and corrosion allowance.

CONCLUSION

Effective management of coated and lined systems under license renewal requires a clear understanding of service environments, degradation mechanisms, and the structural margins necessary to support continued operation. By evaluating coating and lining performance in the context of system chemistry, corrosion rates, and minimum required wall thickness, a technically supported basis can be established for alternative inspection strategies. When appropriately justified, external wall thickness measurements

can provide a reliable indicator of structural integrity while satisfying the intent and conditions of XI.M42 in NUREG-2191.

SIA's nuclear materials and corrosion specialists support utilities in developing these defensible technical evaluations. Through detailed degradation assessments, corrosion rate analyses, and minimum thickness determinations, SIA helps plants establish regulatory-compliant alternatives to certain internal visual inspections. This approach maintains alignment with license renewal requirements while supporting safe operation, improving outage efficiency, and preserving system availability.

Structural Integrity Associates' process ensures adherence to the XI.M42 conditions in NUREG-2191. SIA's robust and comprehensive analytical approach of wall thickness measurements helps plant and asset managers alleviate difficult internal visual inspections while:

- Adhering to auditable regulatory expectations
- Reducing radiation exposure
- Minimizing system out-of-service time
- Improving safety and lessening operational risks

Learn more about SIA's capabilities in our linings and coatings assessment brochure.



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Reducing Vibration-Induced Stress in Small-bore Piping Using Damped Support Systems



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INTRODUCTION

Small-bore piping continues to be a common source of vibration-related issues in operating plants, particularly at socket weld connections on cantilevered drain, vent, and sensing lines. These configurations often include valves or actuators that increase dynamic response and thereby make the weld locations susceptible to high-cycle fatigue.

Industry experience shows that vibration-induced alternating stress at the socket weld toe or root is a key contributor to these failures. Common mitigation approaches include improving the socket weld profile from 1:1 to 2:1 to reduce the fatigue strength reduction factor (i.e., improving fatigue performance) or by adding stiffness through tiebacks or rigid supports. While these methods can reduce vibration locally, they are often time-consuming and costly, require additional calculations and follow-up testing, and may introduce new vibration modes or shift the problem to other locations in the system.

This article examines the problem from a different viewpoint and explores a new mitigation approach based on engineering understanding and lessons

learned from industrial experience. The focus is on evaluating whether a combined stiffness and damping strategy can provide a more effective and practical solution for reducing vibration in small-bore piping systems.

ANALYTICAL SCREENING AND EXPERIMENTAL VALIDATION

The study (1) began with analytical screening. Finite element modeling was used to evaluate several novel candidate mitigation concepts before any physical testing was performed. This approach enabled efficient comparison of different configurations and reduced the time and cost associated with fabricating and testing multiple designs. The models focused on cantilevered small-bore attachments connected to large headers, which are commonly associated with field failures.

The analytical results showed that adding stiffness alone, such as through tie-back supports, can reduce vibration response at a specific location but often introduces additional low-frequency modes at other locations. These modes may be excited by common vibration sources such as blade passing frequency or shear layer-related excitation.

In total, 10 different mitigation concepts were selected and modeled using various finite element techniques. These included clamshell-type supports, wire or cable supports, tie-back structures incorporating viscoelastic or shock-absorbing elements, variations in socket weld joint material properties, and approaches focused on increasing damping using polymer-based viscoelastic materials. The results showed that configurations combining structural stiffening with added damping reduced vibration response over a broader frequency range without introducing unfavorable dynamic behavior. Based on this screening, a steel cone shell support with internal polymer infill was identified as the most effective and practical option and was selected for experimental validation.

To identify a suitable high-damping material, this work was performed in collaboration with the Electric Power Research Institute (EPRI) to evaluate polymer candidates that could provide improved vibration mitigation performance. Damping behavior in dynamic systems is inherently nonlinear, which makes material selection challenging and difficult to predict using analytical methods

alone. For this reason, three candidate polymer materials were selected for experimental evaluation.

The damping behavior of these materials was examined using the well-researched ASTM E756-05 standard method with an Oberst beam test configuration. The samples were tested using both impact excitation and shaker-based random vibration input to characterize their dynamic response over a range of frequencies. The results showed a high level of nonlinear behavior in the damping response of the materials, particularly in terms of energy dissipation across different modes and frequency ranges. For some samples, damping performance varied significantly with frequency, making the response difficult to predict and less reliable for practical application.

One polymer material demonstrated consistent damping performance across the first three bending modes of the Oberst beam and was therefore selected for further use. This polymer was then incorporated

into the cone support design for the small-bore piping application. The cone geometry was developed using 3D scanning of the pipe assembly, and the polymer infill was fabricated using 3D printing techniques to achieve a close fit and consistent material distribution.

A full-scale small-bore piping assembly, representative of a typical vent line, was subsequently fabricated and tested. Modal testing was conducted to validate the finite element model used for vibratory stress analysis. Random vibration testing using shaker excitation showed that the cone-polymer support increased natural frequencies, significantly increased damping, and reduced vibration response and vibratory displacement near the socket weld.

These experimental results indicate that the cone-polymer support altered the system behavior in a way that reduced resonant amplification at fatigue-critical locations and improved overall vibration performance.

VIBRATION AND STRESS REDUCTION RESULTS

Random vibration testing demonstrated reductions in vibrations of up to approximately 46 percent at key locations, depending on direction. The measured excitation data were then used directly as input to correlated finite element random vibration analyses. This allowed stress response at socket weld locations to be evaluated under realistic loading conditions. The combined test and stress analysis results showed a strong reduction in stress response across the dominant frequency range.



FIGURE 1. 3D printed EPU45 polymer cone

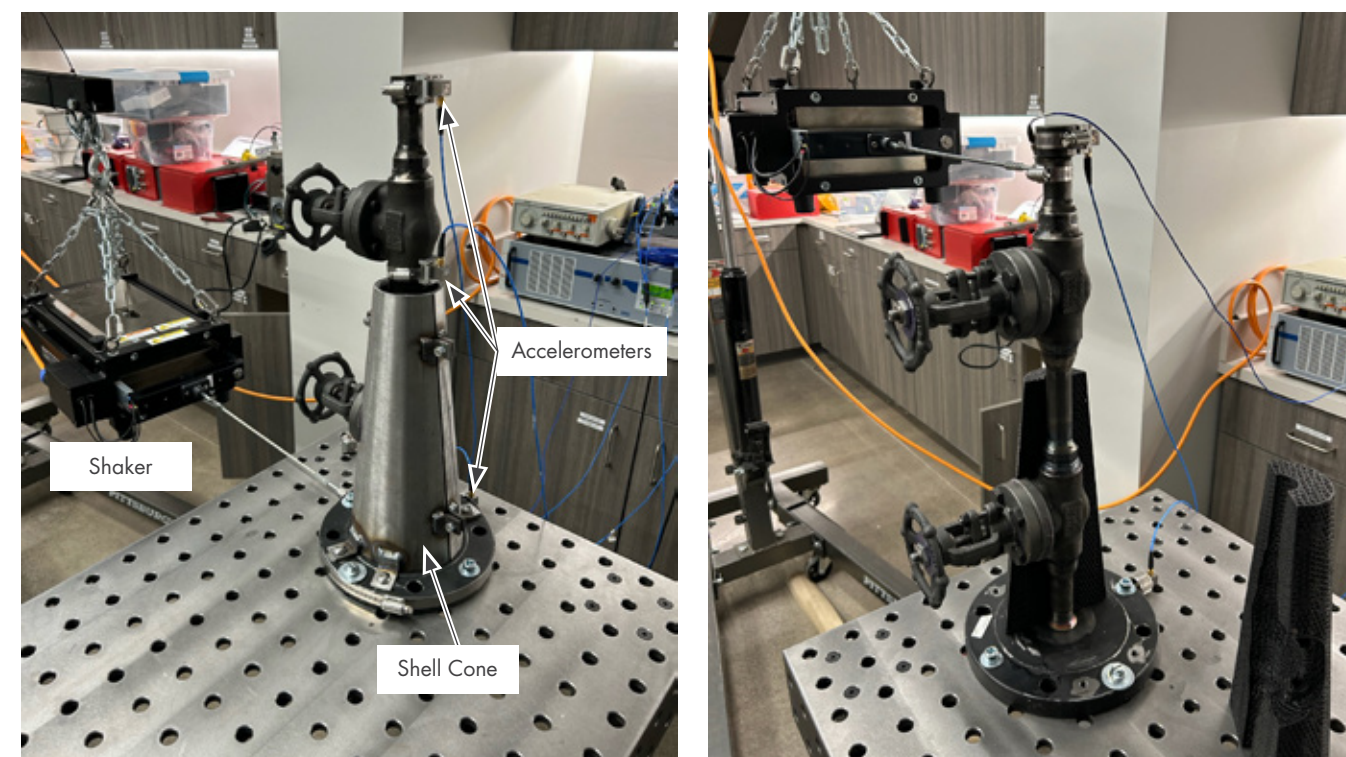


FIGURE 2. Test assembly, cone shell support, polymer infill, instrumentation locations

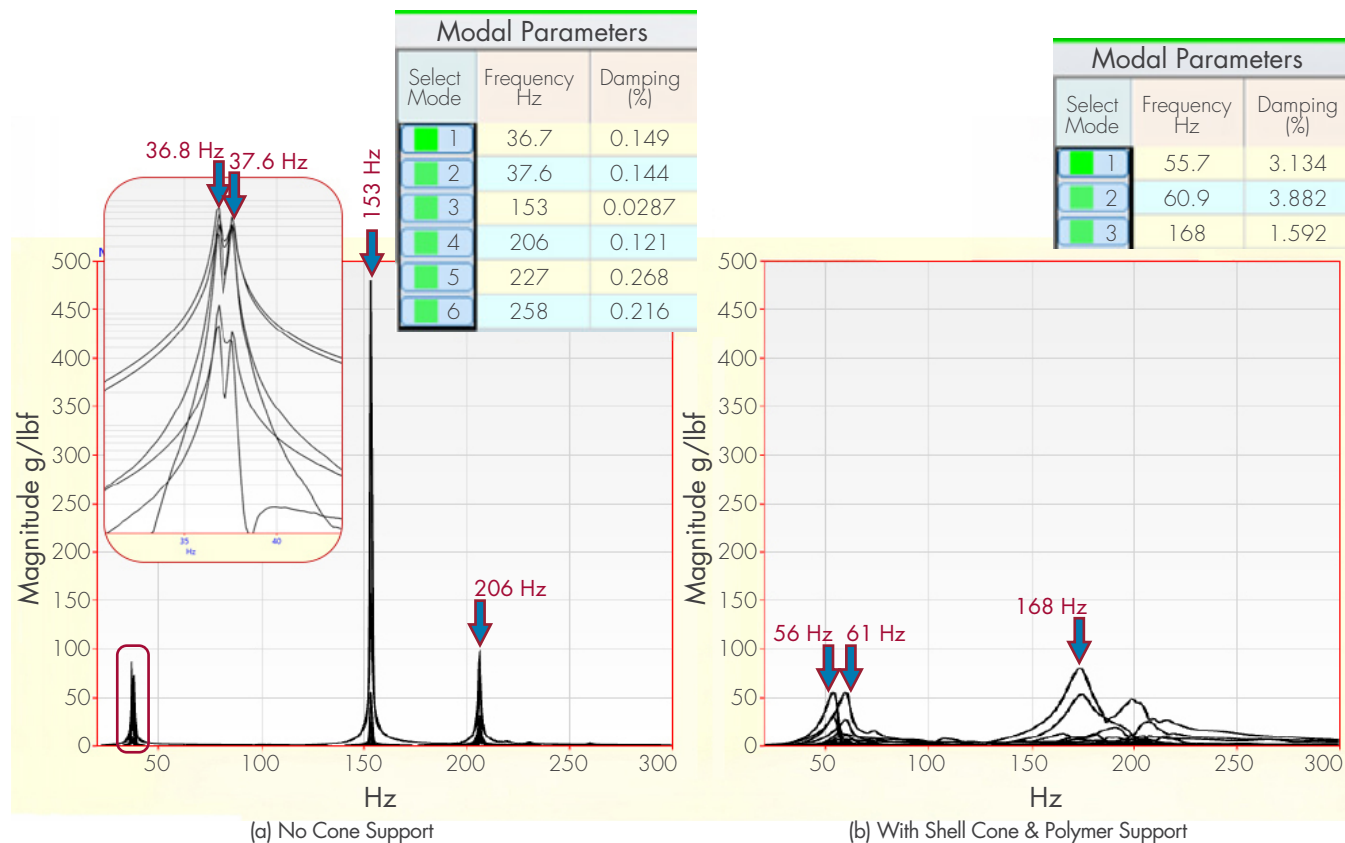


FIGURE 3A. Experimental modal testing of baseline vs cone-supported response, frequency shift, and damping increase

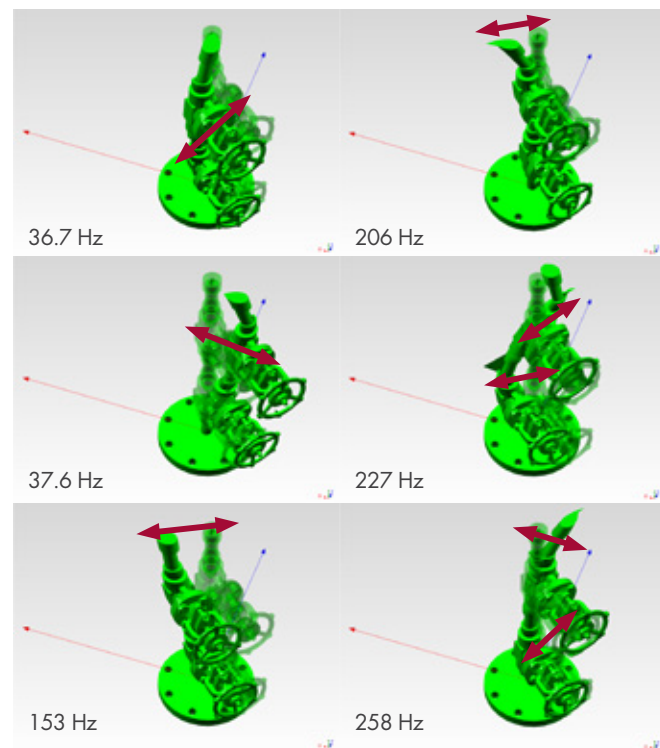


FIGURE 3B. Experimental modal testing of baseline vs cone-supported response, frequency shift, and damping increase

Equivalent stress at critical socket weld locations was reduced by approximately 94 to 95 percent when the cone support was installed.

The analytical predictions followed the same trends observed in the measured vibration data, providing confidence that the observed vibration mitigation translated directly into meaningful reductions in weld stress and fatigue susceptibility.

CONCLUSION

SIA, in collaboration with EPRI, approached a longstanding problem from a different perspective and explored a new mitigation approach grounded in engineering understanding and lessons learned from industrial experience. The results of this effort show that effective vibration mitigation for small-bore piping may be achieved with more than stiffness alone. Combining structural stiffening with damping provides a robust and

practical means of reducing vibration-induced stress at socket weld connections.

By using analytical screening to guide targeted testing, the study reduced development effort while improving confidence in stress-based decisions. The cone shell support with polymer infill evaluated in this work represents a viable passive mitigation option for small-bore piping systems, particularly for retrofit applications in operating plants.

Equally important, this work reflects the value of SIA's active participation in collaborative industry research. Through partnerships such as this one with EPRI, SIA can directly address recurring operational challenges, deepen its technical expertise, and develop practical, field-applicable solutions. These efforts not only resolve specific issues such as small-bore piping vibration but also advance industry knowledge and strengthen the technical capabilities SIA brings to its clients.

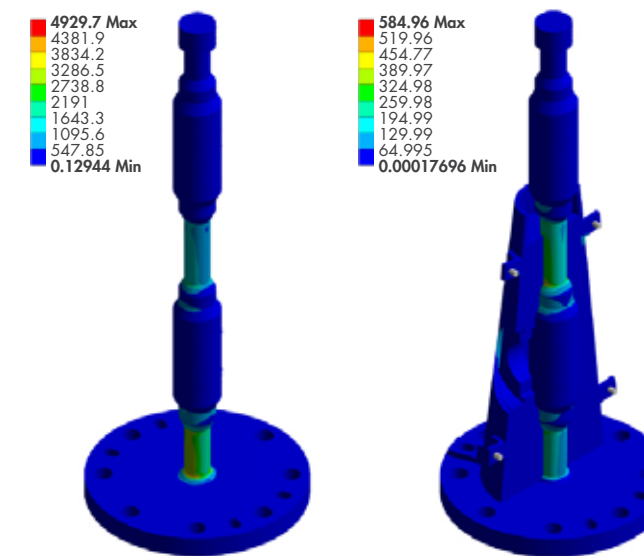


FIGURE 4. FEA-based vibratory stress analysis of a small-bore cantilever pipe under base random vibration excitation using shaker test input. Comparison is shown between the baseline configuration and the cone-polymer supported configuration.

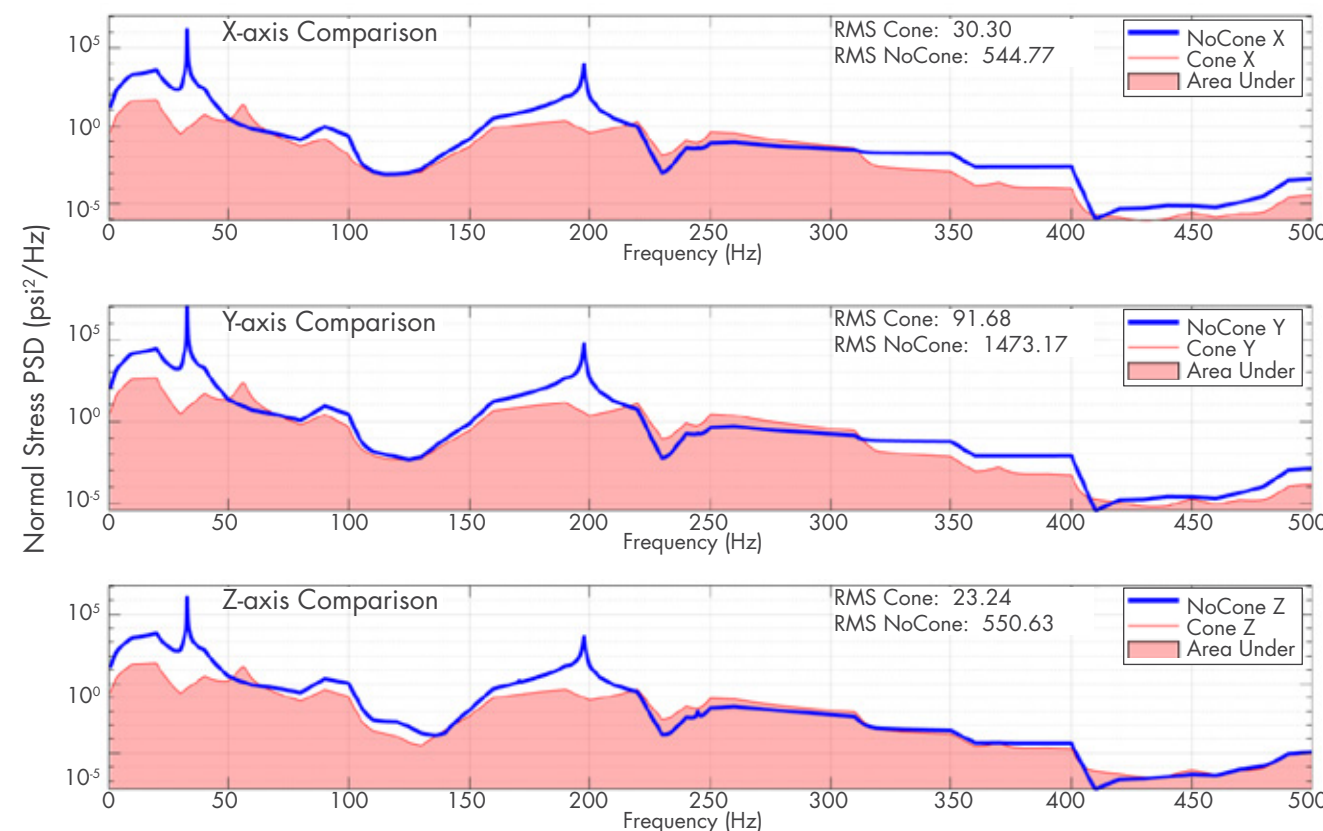


FIGURE 5. Stress at socket weld with and without cone support

ACKNOWLEDGEMENT

^[1] This work was performed by Structural Integrity Associates in collaboration with the Electric Power Research Institute (EPRI), with Stephen Tate as the project manager. The authors acknowledge EPRI's technical guidance and support in advancing vibration mitigation approaches for small-bore piping systems and in enabling the analytical and experimental efforts described in this study.

Seismic Preparedness for Battery Energy Storage Systems



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INTRODUCTION

Battery Energy Storage Systems (BESS) are rechargeable battery systems that can store and distribute energy from various sources. BESS are increasingly used to optimize the electric grid for energy supply and demand, and to support the shift toward renewable energy and a more electrified society. BESS allow energy to be stored when it is cheaper to produce, then released back to the grid when demand and prices increase. Some BESS are being deployed in seismically active regions, making seismic qualification and certification critical to ensure the systems' resilience and prove their structural integrity and functionality after seismic events.

Seismic qualification helps to ensure that BESS can withstand design-level earthquakes without compromising life safety, structural integrity, or operational functionality, depending on the application. Qualification is typically required for modular or containerized BESS units, utility-scale installations, and critical facilities (e.g., hospitals, emergency response centers, substations). These qualifications usually address some or all of the following: structural resistance of the seismic forces, anchorage, and mounting of the frame and internal components to ensure position

retention, post-event functionality, and fire and life safety hazards.

SEISMIC REQUIREMENTS

Different performance levels may be required depending on the codes and standards that need to be met, the seismicity of the project site, and the risk category or critical nature of the facility.

Low seismic regions are defined differently in various codes and standards. These low seismic regions may only require an anchorage position-retention design or even have no seismic requirements at all. Position retention calculations ensure the BESS do not slide or tip during a seismic event.

In moderate and high-seismic regions, structural integrity verification is typically required. Such evaluations ensure that the BESS do not collapse during a seismic event.

Finally, functional verification may be required depending on whether the facility is deemed essential (e.g., hospitals), if the BESS contain hazardous materials, and/or the battery systems need to operate after an earthquake. This functional verification ensures the BESS continue to operate or can be restarted after a seismic event. Grid-stabilizing BESS or emergency backup systems often fall into this category as well.

SEISMIC QUALIFICATION METHODS

Seismic qualification of BESS may involve analysis, testing, or a combination of the two, depending on the complexity and size of the BESS and the risk level of the installation. Experience data generally is an acceptable method for seismic qualification of nonstructural components and equipment. However, rapidly changing battery technology means that the current generation of BESS may not be certifiable using data from previous systems.

Analysis can be used to prove structural integrity and position retention of the BESS. Depending on the code or standard, analyses could be static or dynamic. Static analysis is the default analysis method for the American Society of Civil Engineers' ASCE 7 Standard, and is referenced by the International Building Code (IBC).

For electrical substations, the type of analysis used depends on the size and dynamic behavior of the BESS. Small rigid systems can be evaluated via static analysis. Larger non-rigid systems should be analyzed using dynamic methods, such as response spectrum or time-history analysis. Finite element models are used increasingly, especially for dynamic analyses.



Testing is another method to validate the structural integrity of the system, with one notable difference. Testing is the only way to prove post-event functionality was maintained. This is performed via shake-table testing, which simulates seismic demands by way of input ground motions. Functionality of the equipment is performed before and after the test to verify continued operability.

CODES AND STANDARDS

Depending on the type of facility or jurisdiction in which the BESS will be installed, there may be different requirements for the unit's seismic performance and the seismic qualification method used. The most common codes, standards, and jurisdictions include IEEE 693, the International Building Code, ASCE 7, the California Building Code (CBC), and the California Division of the State Architect (DSA).



IEEE 693 is the standard for Seismic Design for Electrical Substations. This standard applies to electrical equipment installed at substations, including BESS. There are three seismic levels: low, moderate, and high, depending on the substation's location. These seismic levels, along with the manner of construction of the BESS, determine the level of analysis or testing required to demonstrate seismic qualification.

The International Building Code (IBC, Chapter 16) specifies seismic design requirements for all structures, including BESS. This Section states that every structure shall be designed and constructed to resist the effects of earthquakes in accordance with the seismic chapters of ASCE 7.

ASCE 7 details the Minimum Design Loads for Buildings and Other Structures. Depending on the size and construction of the BESS, Chapter 13 for nonstructural components combined with Chapter 15 for nonbuilding structures may apply. These chapters, along with references to other chapters in ASCE 7, define the seismic requirements and loading, performance objectives, and acceptable qualification methods. This includes references to test standards such as the International Code Council's ICC-ES AC156.

The California Building Code applies in California and is based on the IBC, but with some California-specific amendments. The CBC makes similar references to ACSE 7 for defining the structural and seismic requirements of structures, systems, and components such as BESS.

California Division of the State Architect (DSA) oversees approvals for public schools and state buildings. DSA has published an interpretation of regulations notice (IR N-4) that clarifies specific code requirements for modular BESS. Like IBC and CBC, this document relies on ASCE 7 for defining structural calculation, shake-table testing, and other requirements.

While there are codes for other jurisdictions, each with their own requirements, the above standards cover most applications.

STRUCTURAL INTEGRITY ASSOCIATES' CAPABILITIES

Structural Integrity Associates and its subsidiary, TRU Compliance, worked with multiple BESS manufacturers to

qualify and certify their systems for various seismic requirements.

TRU Compliance maintains a network of test laboratory partners across the United States and globally. With this network, we are able to tailor test programs to fit the project's needs in terms of schedule, location, and facility shake-table size. Additionally, Structural Integrity uses industry-leading software packages such as ANSYS and Abaqus™, among others, to accurately model BESS and capture their dynamic performance and structural resilience during an earthquake.

Combining all of these aspects allows Structural Integrity and TRU Compliance to provide a turn-key solution to guide BESS manufacturers and end users through the seismic qualification process and obtain successful outcomes.

CONCLUSION

Seismic qualification of BESS are a multifaceted process involving analysis, testing, and compliance with jurisdiction-specific codes and standards. As BESS deployments grow, adherence to these standards is essential to protecting infrastructure, lives, and grid reliability.

Structural Integrity's team of licensed engineers has expertise and experience with the various codes, standards, and jurisdictions for seismic qualification of BESS. We can help you navigate these requirements and provide the most suitable evaluation method for your circumstances.



www.trucompliance.com

Important Considerations for Successful Failure Analyses



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INTRODUCTION

Failure analysis is essentially a scientific study to determine why a component did not perform its intended function. Often, the component is broken, cracked, deformed, corroded, discolored, or otherwise not in a suitable condition. An evaluation is needed to identify the mechanism of damage and, to the extent possible, the apparent cause of failure. The term failure analysis is occasionally intermixed with root cause analysis (RCA). It is important to distinguish between the two. An RCA is a more in-depth study of causation and often relies on a failure analysis as an individual phase of the broader RCA investigation. The focus here will be on failure

analyses of metal components, which might include pipes, tubes, fasteners, turbine and compressor parts, valves and pumps, shafts, structural components, or even vessels. The process for failure analysis is similar for components made of materials other than metal.

FAILURE ANALYSIS IS VALUABLE BECAUSE FAILURE PREVENTION IS CRITICAL

Failures can cause injury, property damage, lost revenue, or other undesirable outcomes. It is important to investigate failures to learn what action(s) can be taken to mitigate similar failures in the future.

To get the most value from a failure analysis, several considerations are warranted. Some of these apply to individuals who are at the location of the failure event or have access to the failed component(s). Other considerations apply to individuals working in an examination and testing laboratory. The general guidance below, while not an all-inclusive list, should be considered alongside other warranted actions.

IMMEDIATELY AFTER THE FAILURE

1. Document the failed component(s) in-situ.
 - a. Obtain photographs showing the failed component prior to its removal from the service environment to capture information or details that are helpful for the failure investigation.
 - b. Measure critical dimensions that may be helpful for evaluating what-if scenarios.
 - c. Mark samples for reference purposes prior to or during sample removal, but avoid adding paint or ink on fractures, deposits, or other locations of interest.
 - d. Collect and preserve exemplar (unfailed) parts if an examination of these might be helpful in identifying the cause of failure.



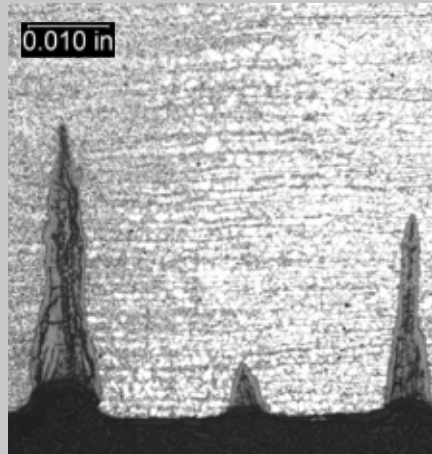


FIGURE 1. Metallographic microscope image of thermal fatigue cracking in a power boiler component.

2. Protect the failed component from further damage or contamination during removal, storage, and shipping.

- a. Keep the sample from getting wet or otherwise contaminated by foreign material that might interfere with analyses of corrosion products or other materials around the component damage.
- b. Avoid wet fluorescent magnetic particle testing (WFMT) and dye penetrant testing (PT) unless absolutely necessary.



FIGURE 2. Fatigue cracking in a splined joint that exhibited excessive wear.

- c. Consider collecting for laboratory analysis any surface deposits present in the failure area.
- d. Avoid excessive heat (e.g., during torch cutting) or unnecessary contamination by metal debris if cutting is required to remove the component(s).
- e. Steer clear of storing samples in locations where condensation can form on metal surfaces.
- f. Protect samples to be shipped to prevent mechanical damage or contamination of features and locations of interest on the sample(s).

IN THE METALLURGICAL LABORATORY

- 3. Document the failed component(s) along with exemplar components, if available.
 - a. Include overall photography, macro-photography, and digital microscopy, as needed. Obtain clear (in-focus) images of the failure region.
 - b. Take measurements or include a scale in the images when appropriate.

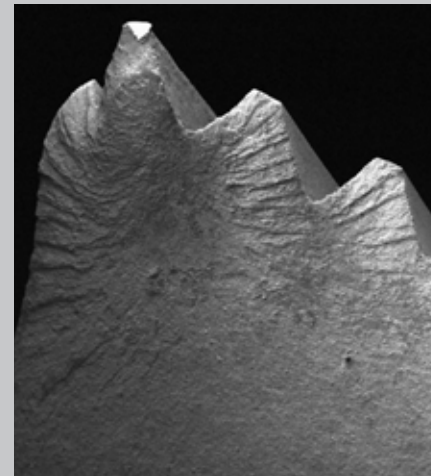


FIGURE 3. Fatigue crack origin area adjacent to internal threads in a generator rotor.

- c. Perform material screening, as needed, using a hand-held positive material identification (PMI) tool via X-ray fluorescence or similar.
- 4. For components that exhibit damage from corrosion, document various characteristics of the corrosion.
 - a. Document whether the corrosion damage is localized or widespread, uniform or irregular, and capture colors that are visible on the sample surfaces.
 - b. Collect deposits from the area of damage and perform appropriate compositional or elemental analyses, such as energy dispersive spectroscopy (EDS).
 - c. Remove a region of damage for in-situ EDS analysis of corrosion products, if necessary.
- 5. For fractured or cracked components, attempt to identify the crack origin location(s).
 - a. Apply focused assessment of the origin site(s).
 - b. Document the component surface adjacent to the origin site(s).

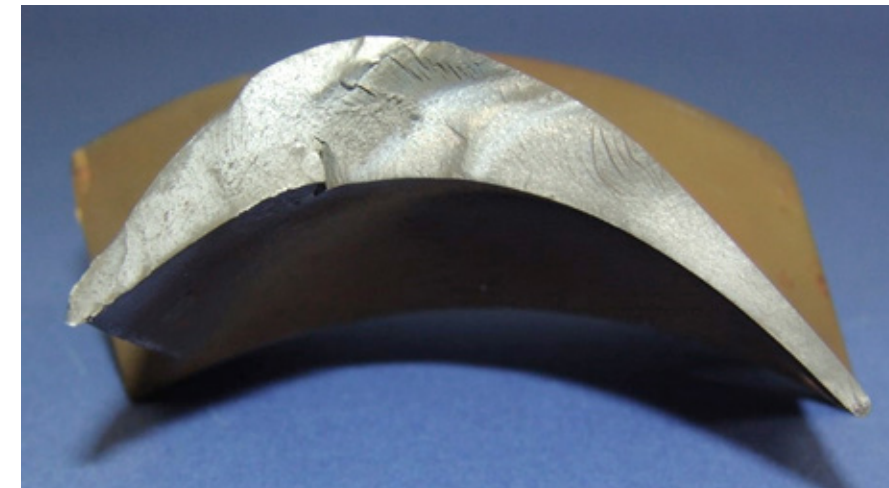


FIGURE 4. Fatigue crack that originated at pitting damage at the trailing edge of a steam turbine blade.

- i. Photograph machine marks, gouges, and other abnormalities or geometric features that could have impacted the crack initiation process.
- ii. Document any secondary incipient cracks.
- c. For closed cracks, consider back-cutting the sample to facilitate opening of the crack to allow for direct fracture surface examination.
- d. When photographing fracture surfaces, apply side lighting to highlight fractographic features.
- e. Use the visible fracture surface features to characterize the failure mode.
 - i. Use macrophotography or digital microscopy to document features indicating fatigue failure, brittle fracture, ductile overload, etc.
 - ii. Check for features indicating an environmental influence (such as stress corrosion cracking).
- 6. Perform energy dispersive spectroscopy (EDS) to analyze the elemental composition of surface deposits, corrosion products, or contaminants and to confirm consistency with the specified component material (alloy).
- 7. Perform scanning electron microscopy (SEM) as needed to evaluate fracture modes by examining fractographic features at high magnifications. Examinations may be performed before or after cleaning of the fracture samples.
- 8. Prepare and examine metallographic cross-sections to assess crack morphology, surface conditions, and overall microstructure.
- 9. Evaluate material properties for comparison to the component's material specification.
 - a. Check the alloy composition against the specified alloy or material using optical emission spectroscopy (OES), or similar.
 - b. Perform hardness testing to confirm expected values, or to assess hard regions at surfaces or in locations where welds are present.
 - c. Perform additional mechanical testing for comparison to specifications (e.g., tensile testing, impact testing, etc.).

After performing all appropriate metallurgical testing, perform a review of the available information to identify or confirm the damage or failure mechanism. Consider historical information about the failed component to help identify the cause of failure. Knowledge of component age, design conditions (pressures, temperatures, etc.), normal operating pressure/temperature, mode of operation (steady state, cyclical, intermittent, etc.), general operating environment, etc., can be useful when investigating failures.

CONCLUSION

The ultimate purpose of the analysis is to accurately identify the reason for failure, then take appropriate actions to mitigate similar failures from occurring. Corrective actions that address the wrong cause of failure are counterproductive and frequently lead to repeated failure events. The overall failure analysis process is most effective when proper steps are taken throughout the investigation, starting with the above considerations.

Structural Integrity Associates (SIA) offers multidisciplinary engineering expertise, advanced analytical capabilities, and decades of field experience necessary to conduct thorough failure investigations that yield actionable insights. Whether addressing a single component failure or developing broader asset integrity strategies, SIA helps clients understand what happened, why it happened, and how to prevent it from happening again. Learn more at our Metallurgical Laboratory web page.



www.structint.com/metallurgical-laboratory

Innovative Seismic Isolation Bearings Strengthen Critical Transportation Infrastructure Across the Pacific Northwest



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INTRODUCTION

Mechanical elements like isolation bearings—including the triple friction-pendulum isolation bearing in Figure 1—provide innovative solutions to complex engineering problems by decoupling structures from damaging ground motions.

Structural Integrity Associates (SIA) has a rich history of providing engineering solutions for structures subject to seismic activity. This article explores two such projects, for which SIA was contracted to provide innovative solutions to challenges facing regional transportation projects.

1. Seismic Protection (Abernethy Bridge)

In high-seismic areas like the Pacific Northwest. Isolation bearings are critical for protecting infrastructure from major earthquakes. When tuned correctly, they allow facilities like the Abernethy Bridge near Portland, Oregon, to remain fully operational immediately following a significant seismic event. Construction is in progress now.

2. Floating Bridge Stability (Homer M. Hadley Memorial Bridge)

While typically used for seismic loads, isolation technology also solved a unique challenge for Sound Transit's East Link extension. To run light rail vehicles from Seattle to Redmond, Washington, USA, engineers used specialized bearings within a world-first track bridge system. These bearings accommodate the multi-directional movement of the I-90 floating bridge, ensuring the rails remain aligned even as the bridge shifts due to lake or weather conditions. Passenger service for the 4-mile, 2 line extension officially opened 3/28/2026.

1. ABERNETHY BRIDGE WIDENING AND SEISMIC RETROFIT

Project Description: The 15-span Abernethy Bridge is 2,717 feet long, carries I-205 traffic across the Willamette River South of Portland, Oregon, and was originally built in 1970 (Figure 2). The original bridge consisted of a steel plate and box girder superstructure, supported by reinforced concrete piers, and foundations of shafts and pile groups.

The bridge is being widened as well as retrofitted for seismic events. The left and right superstructure of the main spans, which cross over

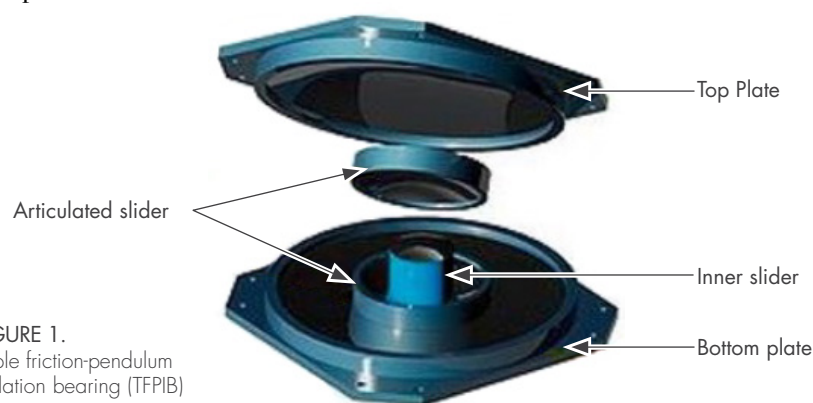


FIGURE 1. Triple friction-pendulum isolation bearing (TFPIB)



FIGURE 2. Abernethy Bridge looking south



FIGURE 3. Water spans - original and widened configuration

water, will be shifted and widened at the center as well as on each of the outboard sides (Figure 3).

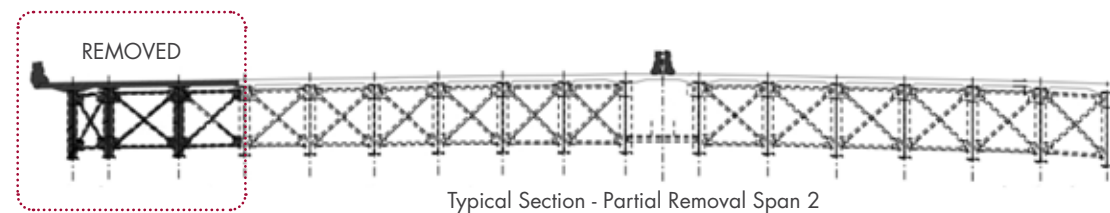
The spans over the land primarily will be widened on the outboard sides (see Figure 4 and Figure 5). The existing steel rocker bearings

were replaced with triple friction-pendulum isolation bearings (TFPIBs). After the widening, there will be a total of 334 new TFPIBs.

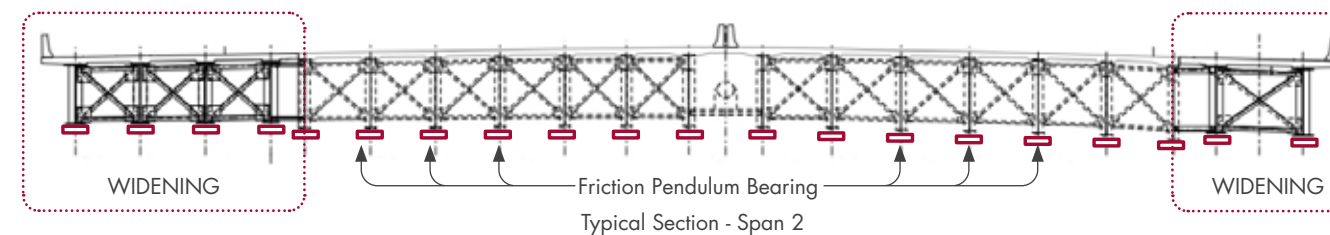
SEISMIC ISOLATORS

For the Abernethy Bridge, the isolation bearings are intended to decouple the response of the superstructure from the substructure during a seismic event to reduce seismic forces into the foundations.

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Typical Section - Partial Removal Span 2
FIGURE 4. Abernethy Bridge - original superstructure cross-section



Typical Section - Span 2
FIGURE 5. Abernethy Bridge - widened superstructure cross section

This improved performance accomplishes three important goals:

- Allows the bridge to withstand severe damage following a major seismic event (1,000-year return period)
- Allows functionality of the facility immediately following a moderate seismic event (500-year return period)
- Significantly reduces the costs of the foundations and supports

ANALYSIS & DESIGN

Ensuring the bridge does not collapse following a major earthquake was the primary goal of the Oregon Department of Transportation. Engineers at Structural Integrity Associates analyzed the bridge using a 1,000-year seismic event and designed the retrofit to mitigate the destructive shaking from the nearby Cascadia Subduction Zone.

Since the bridge is a vital link in the Portland metropolitan area, the ability to have the structure open to traffic after a large earthquake is extremely valuable. The isolation bearings were tuned to dissipate and dampen the seismic energy. This was done by allowing displacement and recentering so that the roadway surface is intact, allowing cars to cross the river.

The bridge foundations are typically the largest cost item when constructing a bridge. In high-seismic areas such as the Pacific Northwest, earthquake forces can easily control the design and cost of the overall structure. Isolation bearings can provide a significant reduction in capital costs for the owner.

The performance of the isolation bearings is tuned through parameters such as dish radius (R1, R2, R3, R4), slider Coefficient of Friction ($\mu_1, \mu_2, \mu_3, \mu_4$), dish size (d1, d2, d3, d4), and dish heights (h1, h2, h3, h4). See Figure 6. The period of the bearing is adjusted by selecting the radius of curvature of the concave surfaces. The damping

is adjusted by selecting the friction coefficients of the slider surfaces.

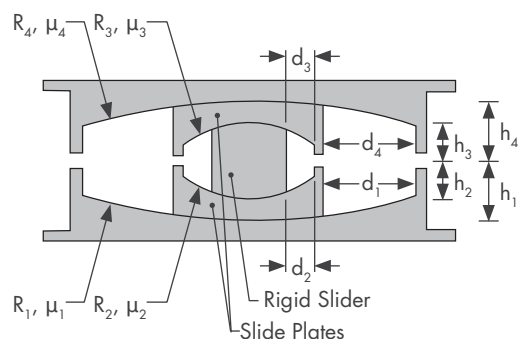


FIGURE 6. Triple friction-pendulum isolation bearing - Abernethy Bridge

Seismic Analysis: SIA developed a detailed 3D finite element model (Figure 7) to evaluate the seismic performance of Abernethy Bridge, using nonlinear dynamic time-history analysis.

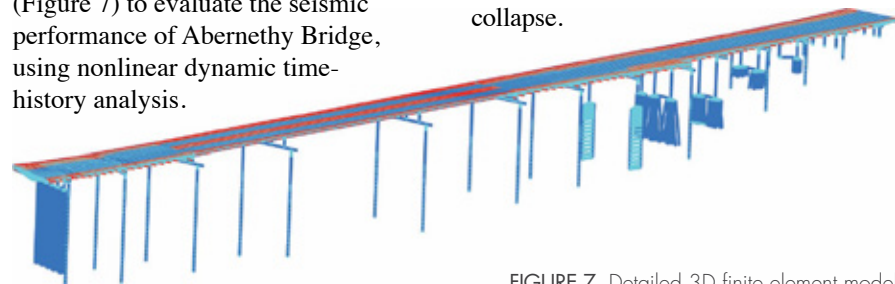


FIGURE 7. Detailed 3D finite element model

The triple friction-pendulum isolation bearings (TFPIBs) were modeled using an implicit element developed and validated (against lab test results) by SIA engineers. All 334 TFPIBs

were included in the global model and evaluated using nonlinear dynamic time-history analysis. A total of twelve 1,000-year and 12,500-year ground motion displacement time-histories were applied to the ground nodes. A sample 1,000-year ground motion time-history is shown in Figure 8. The three different traces represent motion cases with different durations but indicate a maximum permanent displacement of about two feet. These high-ground motions would result in high stresses and strains in the bridge as originally built, with a likely outcome of collapse.

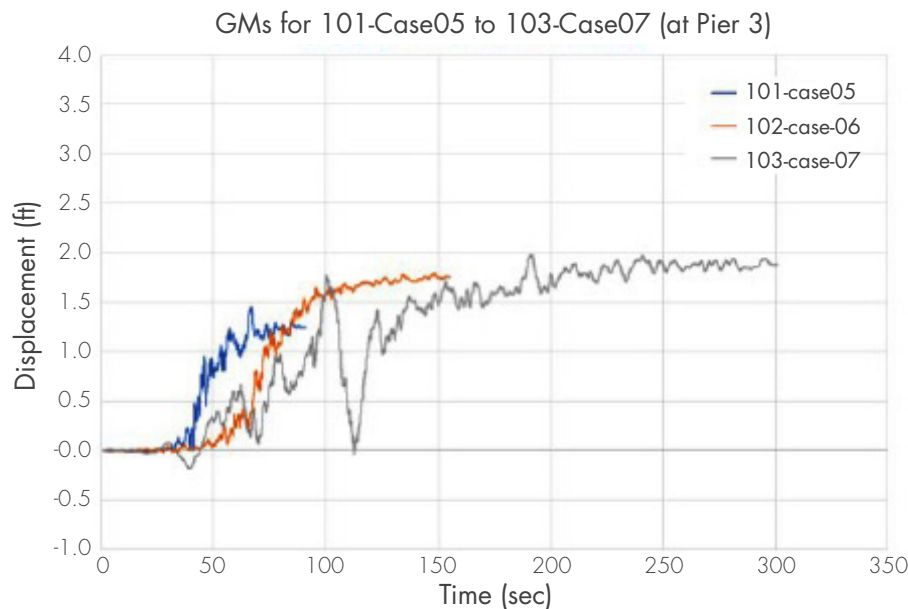


FIGURE 8. 1,000-year seismic ground motion time-histories example

The results of the time-history analysis of the retrofitted bridge yielded the displacement traces at the TFPIBs, as shown in Figure 9. All structural displacements were within the capacity

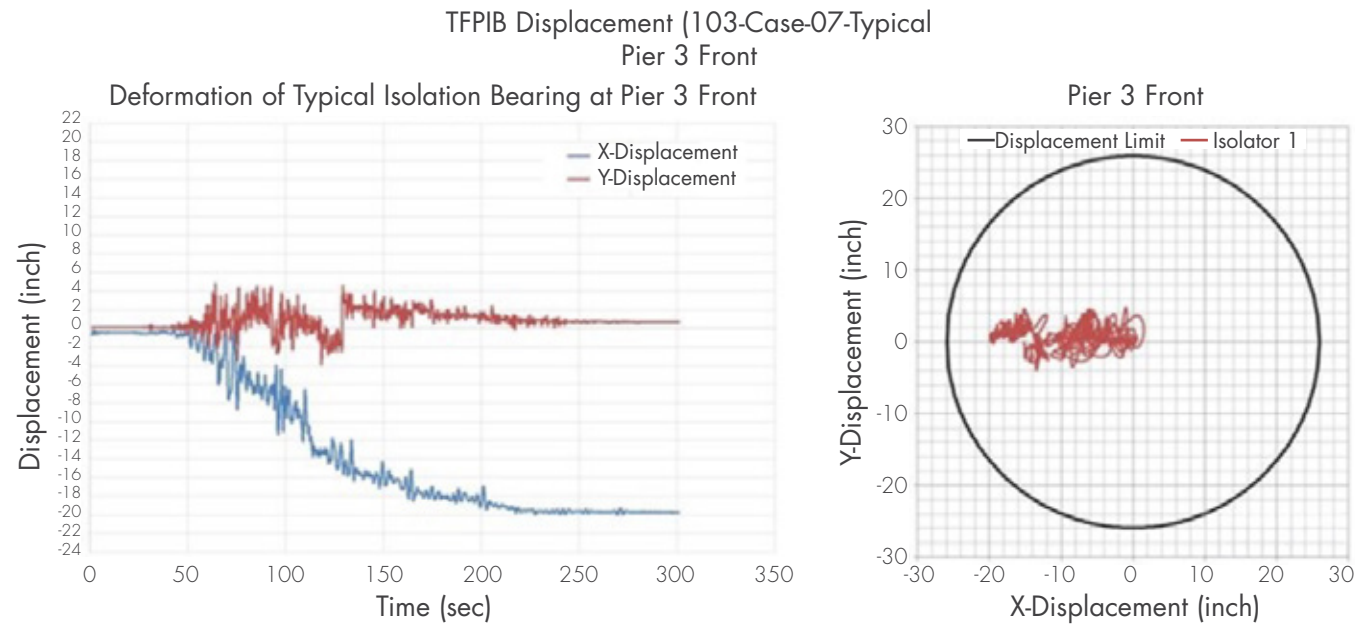


FIGURE 9. Displacement time-history of a typical TFPIB

of the TFPIBs for all ground motions and demonstrated performance that met the design criteria for the project.

COSTS

Typically, for many bridges, the capital cost of using an isolation bearing, such as the friction-pendulum isolation bearing, can be 1-3 percent of the cost of the bridge, if you include design and testing. Additionally, it is standard practice to keep replacement bearings on hand, as the ordering turnaround time is

long. However, the value they can bring is significant due to the cost savings in other elements, such as foundations, columns, and superstructure. Furthermore, there is an economic benefit to keeping the bridge open to traffic following a major earthquake.

2. HOMER M. HADLEY MEMORIAL BRIDGE

Project Description: Interstate 90 (I-90) crosses Lake Washington across the Homer Hadley Memorial Bridge



FIGURE 10. Homer M. Hadley Memorial Bridge



FIGURE 11. Track bridge awaiting installation

(Figure 10), a structure that includes 18 floating pontoons. Sound Transit proposed adding two light rail lines to the I-90 floating bridge as part of its East Link expansion.

This project presented a unique engineering challenge: while cars can easily cross floating structures, operating light rail trains at 55 mph required specialized solutions to prevent derailment. Engineers had to develop a way for trains to transition safely between fixed land-based tracks and a floating bridge that moves in multiple directions.

An innovation called a track bridge (Figure 11) was developed to smooth the track alignment so that movements caused by changing lake elevations, vehicle traffic loading, wind, waves, and extreme conditions could be mitigated. Isolation bearings were a critical piece of the track bridge design because they helped address yaw, pitch, and roll movement combinations of the floating structure.

Eight track bridge elements have been installed on the floating bridge and are being tested. Once testing is complete, rail service is expected to start in 2026.

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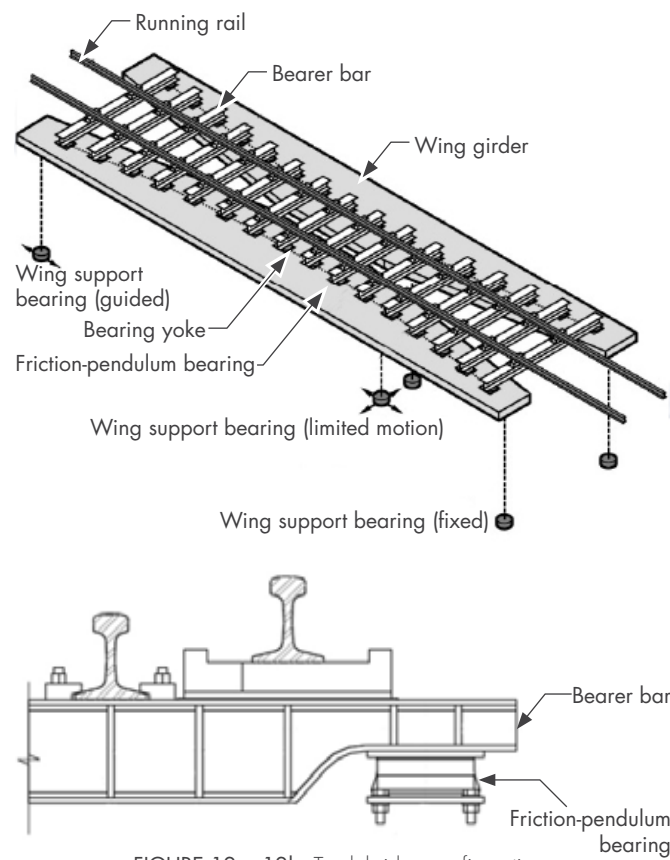


FIGURE 12a, 12b. Track bridge configuration.

The track bridge spans across the bridge expansion joints, and the rail track is supported by bearer bars. The bearer bar rotates about all three axis, with the largest motions occurring about the longitudinal axis of the bridge. Also, the bearer bars displace transversely as the track bridge rotates. There are 34 FPIBs that maintain vertical support for all these movements and allow changes in the rail track profile without significant deformations in the rail. The FPIBs are a critical part of the track bridge mechanism.

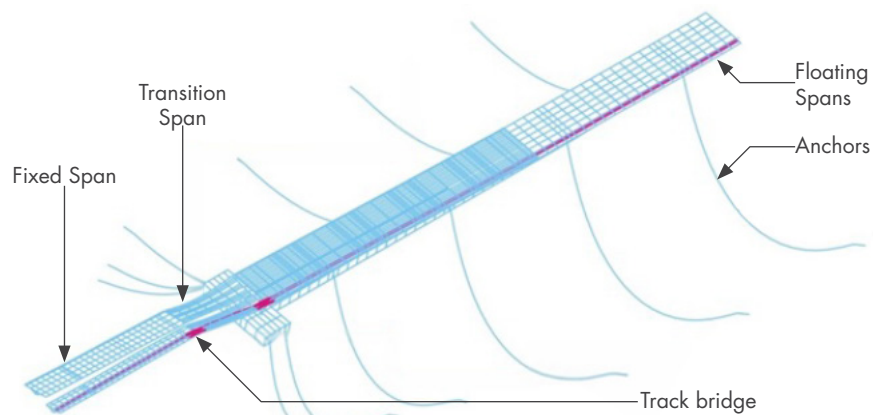


FIGURE 14. I-90 Homer M. Hadley Bridge analytical model

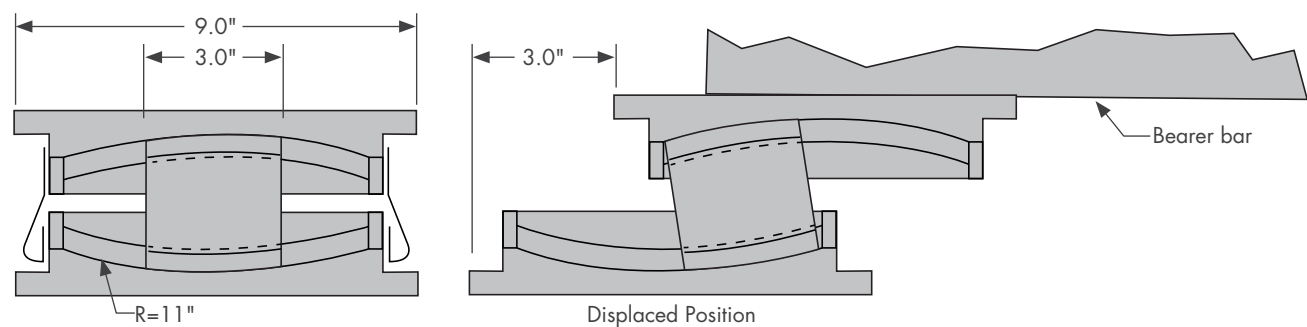
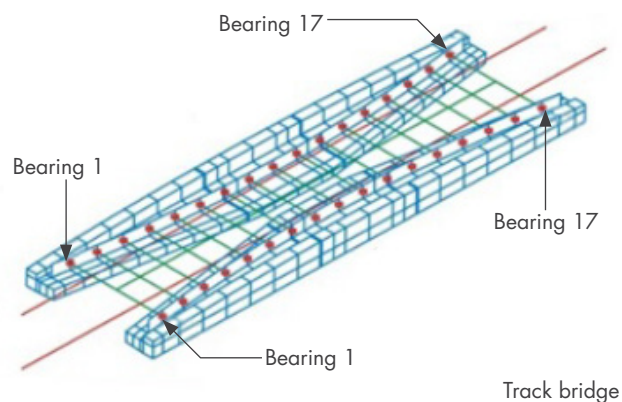


FIGURE 13. Double friction-pendulum isolation bearing - track bridge

MODELING AND ANALYSIS

A 3D detailed finite element model was developed by SIA engineers to evaluate the ride quality and potential of derailment of the Light Rail Vehicle (LRV), using nonlinear dynamic time-history analysis.

The floating bridge, all of its structural components, and the LRV were modeled explicitly and in detail (Figure 14). The bridge FE model included a fixed span, a floating span, and a transition span connecting the fixed span and the floating span. Also included in the FE model are two track bridge structures (one at each side of the transition span), anchors, and a set of nonlinear springs to simulate variable buoyancy forces.



For this project, the double friction-pendulum isolation bearing (DFPIB) was modeled with discrete finite elements as shown in Figure 15.

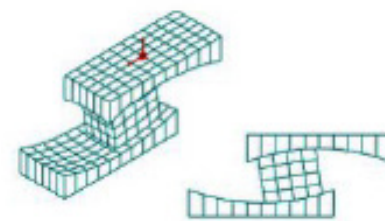


FIGURE 15. Double friction-pendulum isolation bearing analytical model

A construction sequence was analyzed to make sure that the rails were not overstressed due to gravity loads and related bridge deformations. To analyze the performance of the track bridge, the suspension system of the LRV was modeled and moved over the rail of the structural model dynamically through a set of different storm conditions and LRV speeds.

CONCLUSION

When appropriately applied, isolation bearings provide a highly effective strategy for structural resilience under seismic loading. These systems substantially reduce force demands, control displacement response, and limit damage to primary structural components—enabling rapid post-event functionality and supporting continuity objectives critical to modern infrastructure.

Beyond seismic protection, isolation bearings deliver meaningful economic advantages. By managing force transfer mechanisms and redistributing demand more efficiently, these devices can reduce foundation and substructure requirements, often yielding significant construction cost savings.

The projects presented here also illustrate a broader design

opportunity: isolation bearings need not be limited to traditional seismic applications. Where large relative displacements must be accommodated between adjacent structural elements, these devices provide controlled, predictable movement mechanisms applicable to diverse engineering challenges.

SIA's approach to these projects—integrating detailed finite element modeling, validated bearing formulations, and performance-based evaluation—demonstrates our capacity to deliver solutions that are both innovative and analytically rigorous. When critical infrastructure demands the highest levels of structural resilience, SIA provides the specialized expertise required to transform complex technical challenges into constructible, high-performance realities.

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Digital Twin for Semiconductor Process Equipment – Potential and Challenges



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BACKGROUND

In an earlier article in News and Views [1], we described the emergence of digital twins (DT) in the realm of manufacturing. In this setting, a digital twin is a fast, physics-based software model that runs alongside the equipment (physical twin) and is regularly updated by sensor data from the process. The goal of the DT is not to reproduce every detail of the hardware, but to capture the key dynamics with sufficient accuracy to support fault detection, performance assessment, and ultimately predictive maintenance. Figure 1 illustrates this concept.

DTs are beginning to be useful for improving performance and reliability of semiconductor manufacturing equipment [2]-[4] used for integrated circuit (IC) fabrication. This includes

rapid thermal processing (RTP) which is used in several key steps of wafer processing. Yield loss in chip fabrication may occur due to several reasons including sensor failure, actuator (lamp) failure, gas flow failure, or sensor drift. Identifying the root cause of the problem can be quite challenging. A physics-based DT model may provide insights needed for fault detection and ultimately, predictive maintenance.

This article focuses on one practical question: how far can a physics-based DT help diagnose faults in an RTP tool? We examine three classes of problems. The first is sensor fault detection – an area which is relatively mature and can be handled effectively with a bank of Kalman filters. The second is failure detection for the actuator, or heating lamp in RTP systems, which is more

challenging because the thermal effects are distributed and strongly coupled. The third class is detection of changes in model parameters caused by changes in material properties, which are the hardest to diagnose but will negatively affect system performance.

RAPID THERMAL PROCESSING (RTP)

Rapid thermal processing systems are used for several high-temperature semiconductor wafer processing steps, including implant anneal, dopant activation, silicide formation, and thin dielectric processing. In RTP, the wafer is heated rapidly to the process temperature and then cooled following a prescribed temperature trajectory. In implant annealing of silicon wafers, the latter is heated to 1050°C over a few seconds. This heat treatment anneals any stresses incurred during ion implantation of dopant species, and also activates the

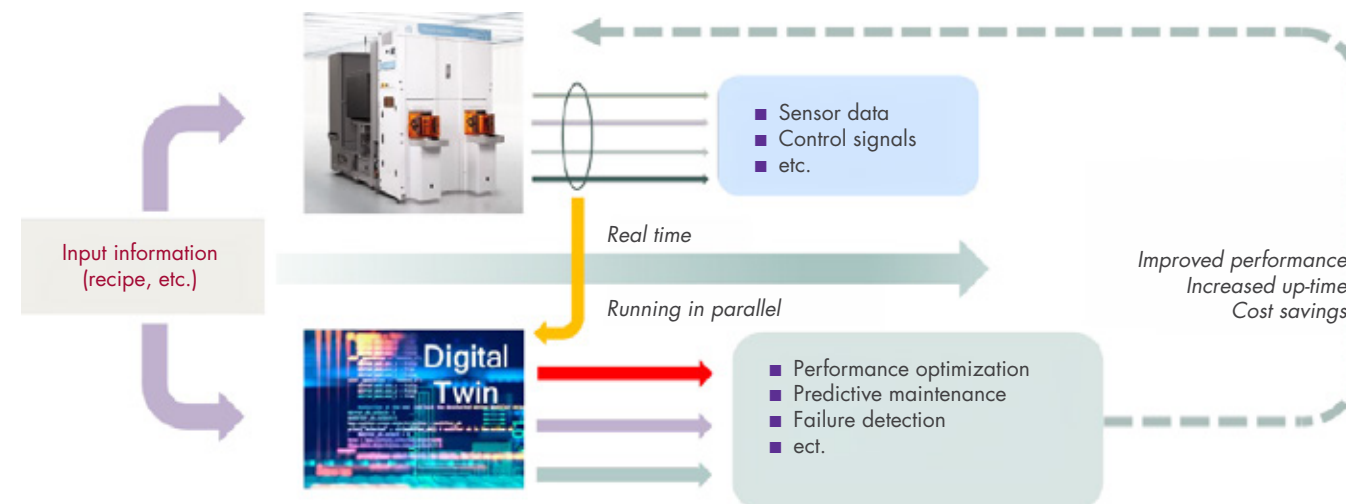


FIGURE 1. Schematic of a digital twin deployed for semiconductor equipment.

implanted ions resulting in the formation of transistor junctions in the integrated circuits. The process requires that the temperature non-uniformity be less than 5°-10°C during ramp-up and cooldown, and less than 1°C in the processing period, over the entire surface of 300mm diameter wafer. Such tight non-uniformity is needed to prevent warping or crystal slip in the wafer that is less than 1 mm thick. These stringent requirements place extreme demand on both heating speed and temperature uniformity. Even if the wafer temperature is kept uniform at the five or six measurement locations the temperatures at other locations on the wafer could be far from the process temperature which would warp the wafer into a giant potato chip! This is where a DT that uses a physics-based model acts like a virtual sensor, monitoring the temperatures over the entire wafer, and helping the controller maintain tight uniformity everywhere on the wafer – not just at the few measurement locations.

SC Solutions has longstanding experience in RTP modeling and control [5], [6], and licensing such control software to the OEM’s forms the core of our business. The discussion below uses a generic RTP chamber to show how that modeling foundation can be extended into a DT for monitoring and diagnostics.

MODELING AND CONTROL FOR RTP

We will use a generic RTP system geometry as shown in Figure 2. It incorporates the key elements of commercial RTP systems (a picture of which is shown on the left of Figure 3), albeit with geometric simplifications such as assuming axial symmetry. The chamber contains 14 lamp rings above the wafer, highly reflective cooled walls, and quartz components that transmit the short-wavelength radiation used to heat the wafer and edge ring. The model predicts the nonlinear thermal response of the system (i.e.,

the transient temperature distribution) and forms the core of the DT. Technical details of the physics-based model and controller development process of such a representative RTP chamber have been published elsewhere [6].

A physics-based model of RTP for a DT is challenging because of the trade-off between physical model accuracy and execution speed.

A sufficiently accurate model of radiative transport, the dominant mode of heat transfer (see Figure 2) may take a long time to run while the DT must run in real time. Additionally, the large range of temperatures requires the use of temperature-dependent thermal properties. **SC Solutions has developed the software and methodology to build fast, low-order models that are sufficiently accurate for precise temperature control.**

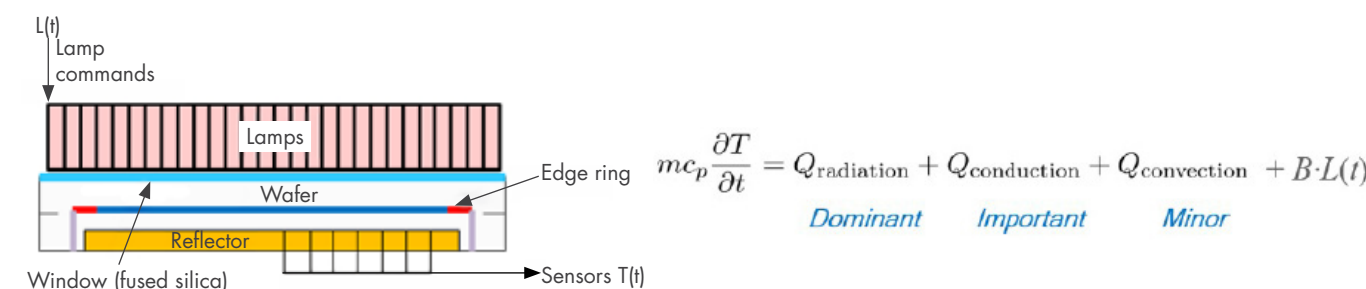


FIGURE 2. Left: Cross-section of an RTP system. Right: governing heat transfer equation.

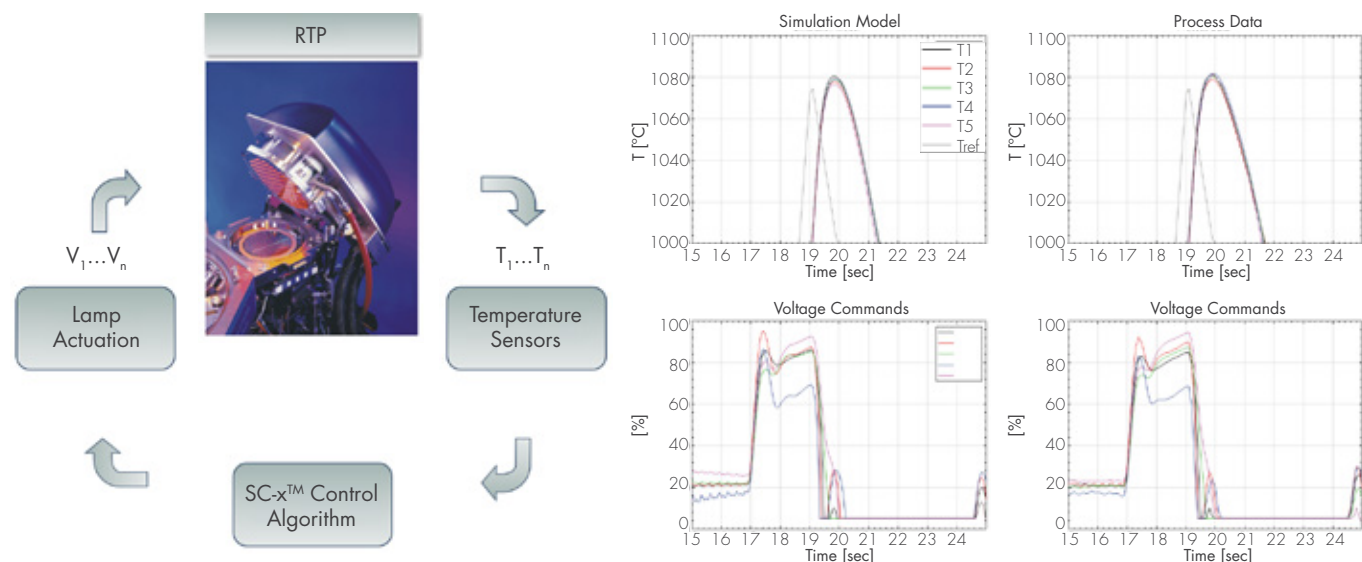


FIGURE 3. Left: Closed-loop control of RTP. Right: Comparison of model prediction with commercial tool data

RTP control is challenging because radiation is the dominant heat-transfer mechanism, which is highly nonlinear over the operating temperature range. The controller is multivariable—multiple sensors measure wafer temperature at different radial locations. The system is also strongly coupled with lamps heating overlapping areas on the wafer: together shaping the temperature profile. A controller therefore has to account for interaction among multiple lamp zones rather than treating each loop independently. Hence, a Multi-Input Multi-Output (MIMO) control design solution is needed.

The chamber also contains components with very different thermal time scales. Lamp filaments respond quickly to changes in power command, while quartz components like the window respond more slowly. That spread in dynamics makes open-loop prediction insufficient for the high accuracy levels required for fabricating IC chips, which is why closed-loop control is essential.

Figure 3 (Left) shows the closed-loop framework used here. A multivariable feedback controller corrects modeling errors, rejects disturbances, and handles actuator limits. **In our RTP work, linear quadratic Gaussian**

(LQG) control has been most effective because it naturally handles multivariable interaction, measurement noise, and integral action within a single framework.

Figure 3 (Right) compares the model response with data from a commercial tool. The excellent agreement makes the model useful not only for control design, but also for digital-twin-based monitoring and diagnostics.

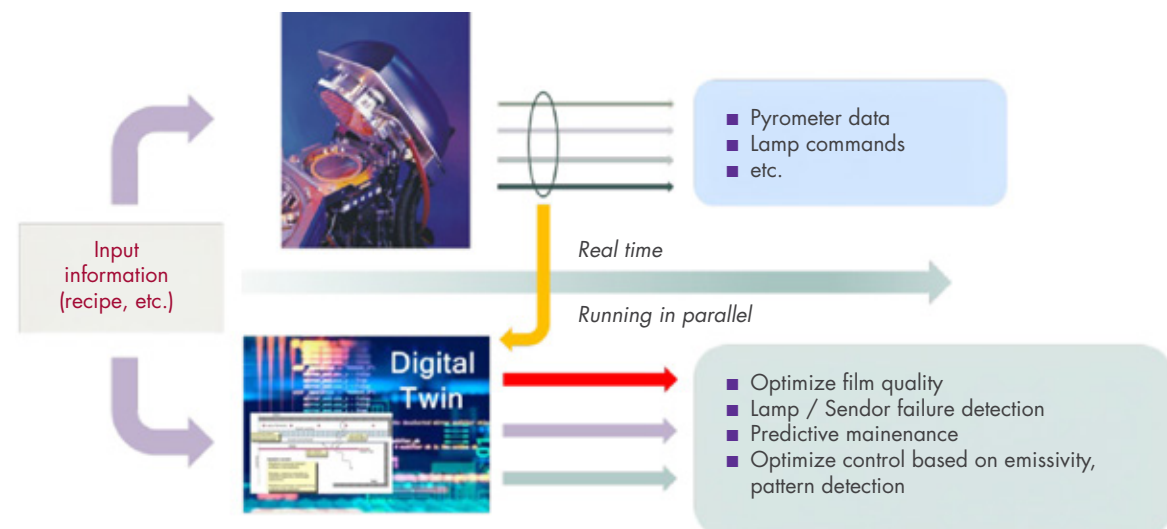


FIGURE 4: Digital twin framework for rapid thermal processing (RTP).

DIGITAL TWIN FOR RTP

For RTP equipment, a DT can support several functions such as monitoring process performance, detecting sensor and actuator faults, estimating hidden or inaccessible states (virtual sensing), and providing information that may be useful for predictive maintenance. Figure 4 summarizes these roles.

In this article, we concentrate on fault detection, isolation, and recovery (FDIR) for an RTP process. There are three categories to consider:

1. Sensor faults using a bank of Kalman filters (BKF).
2. Actuator faults using a disturbance observer (DO).
3. Parameter excursions using a combination of BKF and DO concepts.

These three categories are not equally difficult. Sensor faults are often the most tractable because they can be detected in the measurements using BKF. Actuator faults are harder because their effects are distributed across the thermal field. Parameter excursions are harder still because they may influence the process only indirectly. We discuss only the first two categories in this article.

DIGITAL TWIN: SIMULATION & DETECTION SETUP

To evaluate these ideas, we created a simulation environment that mimics an RTP tool operating in closed-loop, as shown in Figure 5. The plant (RTP chamber), actuators, and sensors are represented by the previously developed physics-based model. The model-based multi-input multi-output (MIMO) feedback controller that was designed and implemented drives the system using noisy temperature measurements. The digital twin runs in parallel in real time. It receives

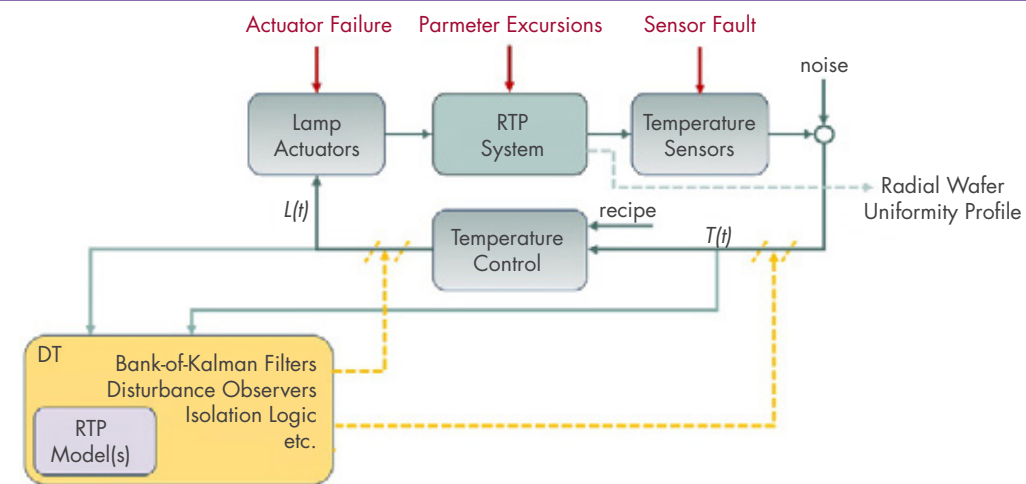


FIGURE 5. Schematic of use of Digital Twin (DT) for fault detection, isolation, and recovery (FDIR).

the same inputs and measurements and applies diagnostic logic to determine whether the observed behavior is consistent with normal operation or with a fault scenario. To monitor and display different signals during simulation, we created a composite graphical display to show various signals as well as a ‘health dashboard’.

SENSOR FAULT DETECTION USING BANK OF KALMAN FILTERS

A bank of Kalman filters is a practical way to detect sensor faults [7]. In simple terms, a Kalman filter is a running estimate of how the system is behaving. At each instant, it blends

two pieces of information: what the model predicts should happen next, and what is actually happening as reported by the sensors. Because real measurements always contain noise to varying levels, the filter does not follow the sensors blindly. Instead, it combines model prediction and measurement together to produce the best estimate of the system state. In a bank-of-filters approach, several such estimators run in parallel, each representing a different fault hypothesis, as shown in Figure 6. The hypothesis whose prediction best matches the measurements points to the most likely faulty sensor.

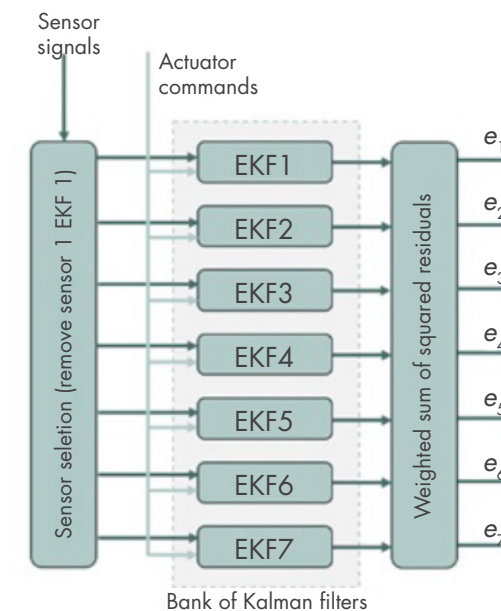


FIGURE 6. Schematic of a bank of Kalman filters.

Using our low-order RTP model, we constructed a bank of Kalman filters for the seven temperature sensors. The example below shows a representative case in which a large bias is introduced into one sensor and the DT identifies the fault and supports recovery through estimator-based substitution of the failed measurement. The example illustrates two important points. First, the digital twin can identify which sensor is inconsistent with the rest of the system. Second, once the fault is isolated, the estimator can provide a temporary virtual measurement so the process can continue until maintenance is performed.

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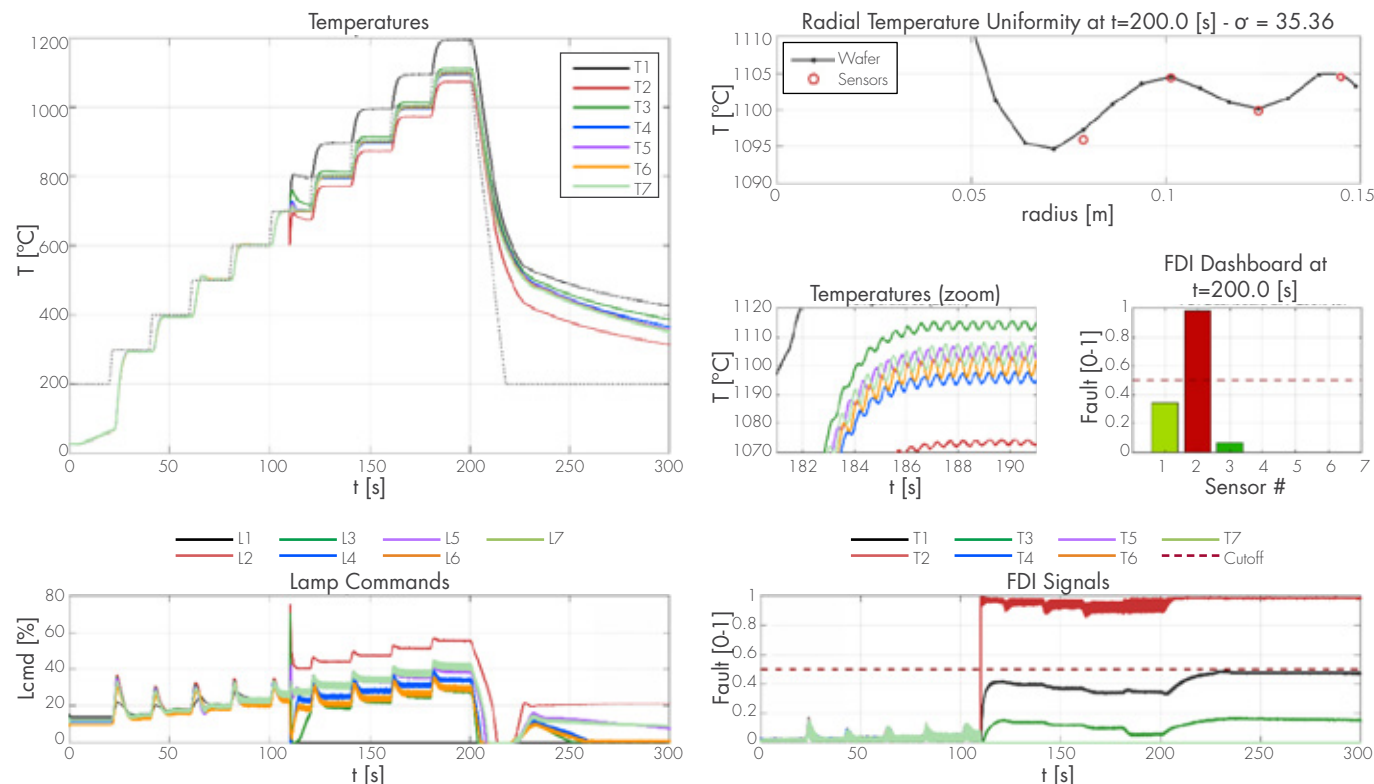


FIGURE 7. Sensor fault detection and accommodation using a bank of Kalman filters – detection of -100°C fault on Sensor #2.

ACTUATOR FAILURE DETECTION USING DISTURBANCE OBSERVER

Actuator fault detection is addressed here with use of a disturbance observer. A simple way to think about this method is that the DT estimates how much heat the lamps should be producing based on the power input and compares that expectation with what the wafer temperatures indicate based on what is actually

happening in the chamber (see Figure 8, Left). The difference behaves like an estimated disturbance which is fed back to the control input as indicated by the dashed line. When interpreted carefully, that disturbance estimate can indicate a loss of actuator effectiveness [8], [9].

This problem is more difficult than sensor-fault detection because the

chamber has 14 heater zones (Figure 8, Right) but only seven temperature sensors. In other words, the available measurements do not directly reveal every actuator’s condition. Good calibration and the use of an accurate nonlinear model for the DT is therefore crucial if a disturbance observer is used for detecting actuator failures.

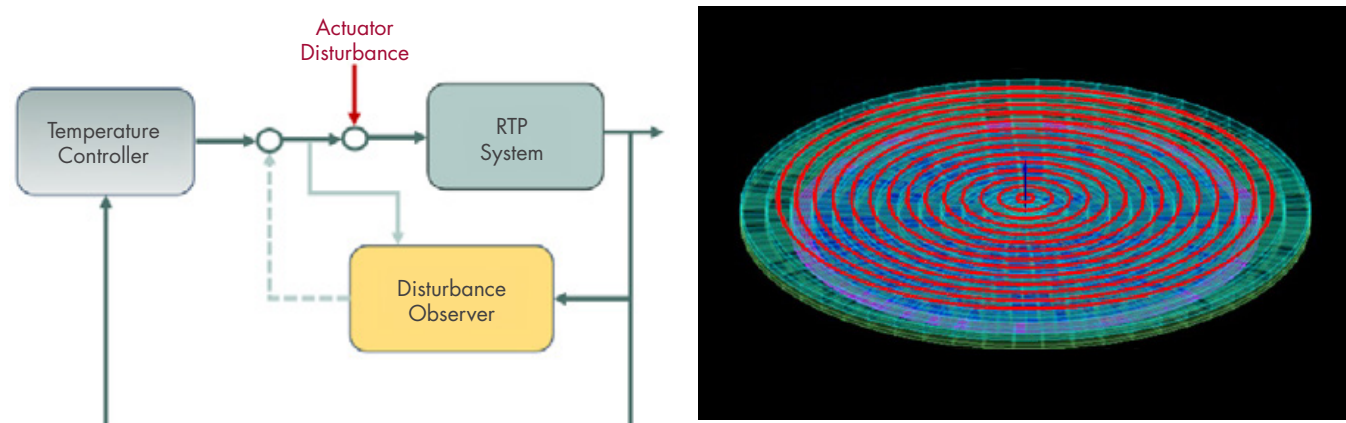


FIGURE 8. Left: Block diagram of disturbance observer in conjunction with standard temperature controller. Right: Lamp grouping for fourteen-zone lamp configuration.

The results of our studies show that a disturbance-observer approach can detect large actuator losses and provide useful diagnostic information even when multiple zones are involved.

- Large actuator losses can be detected reliably, including partial and full loss of lamp power.
- With a well-calibrated nonlinear model, the method can infer more actuator information than the raw sensor count alone would suggest. The DTs physics-based model is especially important because actuator effects are strongly coupled across the wafer.
- Even when isolation is incomplete, the disturbance estimate still provides useful maintenance information.

Its limitations are also important:

- Measurement noise affects thresholds and therefore detection sensitivity.
- Model uncertainty and unrelated parameter changes can appear similar to actuator faults if calibration is poor.
- Coverage improves when the

observer is evaluated for those actuator failure modes that matter most in practice.

- Recovery logic is application-specific and generally more difficult than detection alone.
- SUMMARY AND FUTURE DIRECTIONS**
We examined three digital-twin concepts for FDIR in an RTP system:
- Sensor-fault detection using a bank of Kalman filters.
 - Actuator-fault detection using a disturbance observer.
 - Parameter-excursion detection using a combination of both ideas.

Overall, the results of our investigations are encouraging, but they also reveal the ways in which current methods still fall short:

- Sensor noise limits how small a detectable sensor fault can be.
- Model uncertainty is a major factor in actuator-fault detection.
- Parameter excursions remain the most difficult class because they are often only weakly visible in the available measurements.

This set of capabilities is the basis of the promise of DTs’ use in predictive maintenance of semiconductor wafer processing equipment by helping engineers detect future faults before they lead to unscheduled downtime that must be avoided.

The primary lesson here is that for digital twins of semiconductor equipment to be useful for routine use in preventive maintenance in fabs, the underlying dynamic models must not only be fast (simulations run faster than real time), but the simulation results must also be sufficiently accurate for nuanced interpretation. For RTP, physics-based models can already support meaningful fault-detection functions, especially for sensor faults and larger actuator losses. The more subtle the degradation mechanism, however, the more challenging the diagnostic problem becomes.

This challenge defines the frontier of SC Solutions’ active research – and they are uniquely positioned to advance it, combining rigorous physics-based modeling with decades of validated RTP control implementation in commercial semiconductor equipment.

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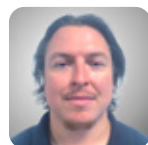
Siemens 13.9m² Disk Bore Keyway Nondestructive Examination Re-development

SIA's Holistic Approach to Rotor Life Assessments

Structural Integrity Associates validated automated PAUT to achieve 100% disk bore/keyway coverage on Siemens 13.9 m² rotors—within a predictable five-day outage—supporting defensible life assessments without de-stacking.



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INTRODUCTION

The Siemens retrofit 13.9 m² rotor is a 1,800 RPM double-flow, low-pressure (DFLP) turbine rotor commonly used by nuclear utilities for power generation. This rotor is a built-up design, meaning it has a shaft with three shrunk-on wheels (or disks) per flow (at each end).

Like its disk-rim blade attachments, the shrunk-on disk-bore/keyway regions on 13.9m² rotors are susceptible to intergranular stress corrosion cracking (IGSCC). This is due to high-stress concentrations inherent with the specific geometry and steam cycle chemistry. Poor water chemistry or fabrication-type discontinuities introduced during rotor assembly cause pits. These pits can facilitate the initiation of cracks during the unit's operation. Nondestructive examinations of the rotor should

include the complete rotor periphery (Steampath), L-0 stage blade roots, disk rim blade attachments, and shrunk-on disk bore/keyways, using appropriate examination techniques.

The shrunk-on disk bores are a key component in assessing a rotor's viability for continued operation. A thorough evaluation of that region must be performed using a suitable inspection technique that most accurately detects and characterizes in-service damage in the bore region. Without disassembly of the rotor, the only viable way to interrogate the disk ID and keyway surfaces is by using an ultrasonic method. An automated phased array UT (PAUT) ultrasonic technique allows for post analysis and peer review of the data and is an industry best-practice endorsed by EPRI.

Despite being the right technique, performing PAUT inspections of

the disk bore region does come with inherent limitations. These limitations may include managing complex, uneven surface geometries, including minor geometric variations between rotors that often arise. Attenuation of the ultrasonic sound beam due to long travel distances (sound-path) is also a concern, as are potentially minor variations in material properties. These limitations combined make achieving 100 percent coverage at the disk-bore region challenging. However, without 100 percent coverage, the inspection provides limited data, reducing the NDE information available to support an engineering rotor life assessment. Recognizing this challenge, Structural Integrity Associates (SIA) proactively undertook a redevelopment of its disk bore inspection protocol in 2023, with the specific goal of achieving 100 percent examination coverage across all six disk bore regions on Siemens 13.9 m² rotors.



The task at hand was 1) to develop an inspection protocol that would ensure 100 percent coverage of all six disk bores without compromising sensitivity, despite minor variations between rotors, and 2) to build proven contingency options to address one-off situations like local geometric variations or attenuation issues that inevitably arise.

TECHNIQUE DEVELOPMENT

To detect discontinuities propagating from the disk bore and keyway regions, an automated PAUT technique is employed. Demonstrated multi-element search units are directed at the normal angle to the bore, enabling detection of radial-axially oriented cracks at the bore surface and keyways.

SIA started by developing detailed CAD models of the rotor, including the shaft and disks. Using CIVA advanced ultrasonic modeling software, they began the arduous process of evaluating numerous probe wedge combinations, even trialing theoretical probes. Keeping in mind component geometry, material properties, and sound-path distances, they set out to determine the best combination of ultrasonic coverage, inspection sensitivity, flaw detection capability, and interpretation of results for each of the three disks per flow.

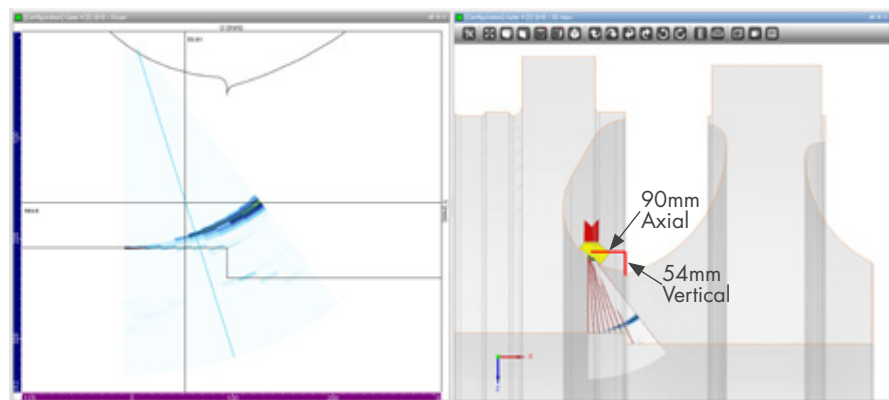


FIGURE 2. Example of detail in probe placement for optimal detection

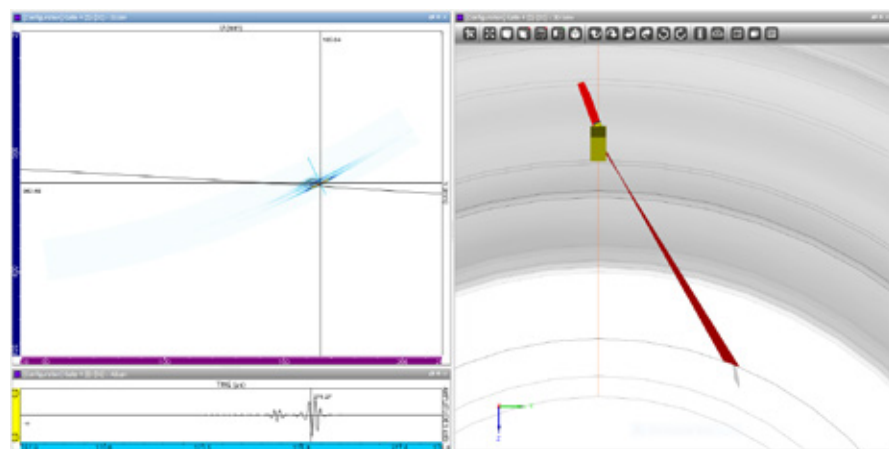


FIGURE 3. Example of detection capability on a 3mm x 6mm elliptical flaw

Beam plots were used to determine how the ultrasonic coverage would be achieved. This was followed by beam computations to show the

resulting ultrasonic field for every combination of probe and focal laws. These modelling tools enabled SIA to compare probe parameters such as frequency, element size, wedge angle, focal laws, etc., on numerous probe/wedge/combination combinations. After determining the theoretical best options, simulations were then modelled to validate results and determine flaw size detectability.

Disk-specific probe placements were calculated, trialed, and validated for each probe, at each disk and hub surface. Also, contoured wedges were designed and modeled to allow for multiple scan directions at each specific inspection location.

Next, simulated flaws were embedded in the models to determine ultrasonic responses. The desired and resultant detection capability was to distinguish a

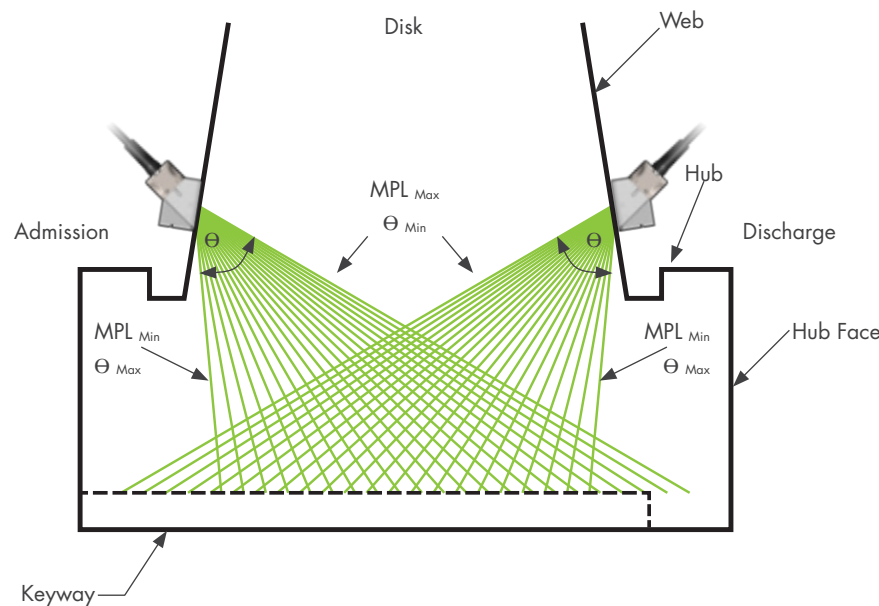


FIGURE 1. Turbine disk web scan nomenclature (Side View)

3mm x 6mm elliptical flaw at the center of the disk, with detection improving as the flaw approached the ends of the disk.

THE RESULTING PROTOCOL

Following months of modelling, scan simulations, and iterative adjustments, SIA's redesigned disk bore inspection protocol used a series of customized probe/wedge combinations placed at optimized locations unique to each disk. Using multiple wedges, the beam was aimed in three directions at each location: normal to the bore surface, tangential to the bore surface clockwise, and tangential to the bore surface counterclockwise.

To ensure full coverage with overlap, this new protocol requires a minimum of 17 unique probe placements, collecting at least 51 360° scans per flow, or 102 scans per rotor. Additional scans will be collected as needed to account for local variances. This redeveloped protocol ensured 100 percent coverage of all six disk-bore surfaces. By capitalizing on well-thought-out probe placement locations and angles, overlapping coverage across all high-stress regions was achieved. In the event of attenuation issues, a large-aperture, large-

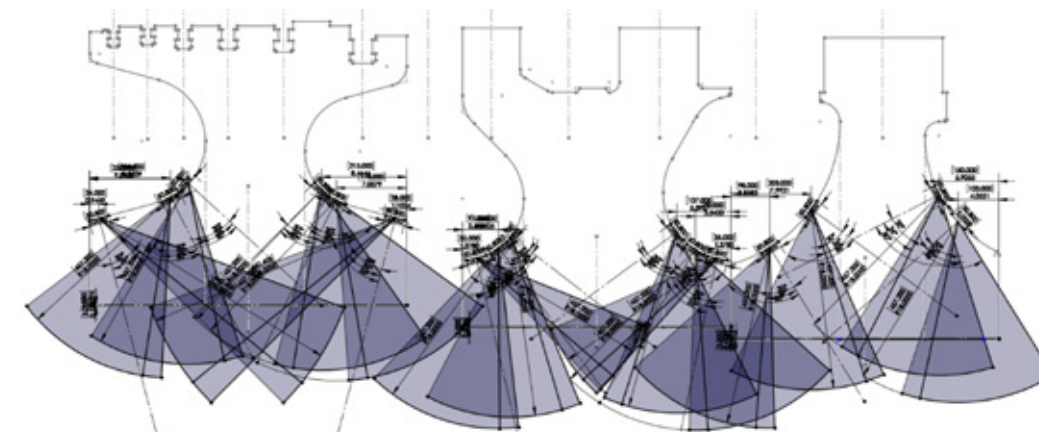


FIGURE 4. side view showing probe placement and coverage overlap for all three wheels per flow

footprint probe designed to punch through attenuative or geometrically challenging materials was designed, tested, and implemented as a contingency plan.

The redeveloped protocol was then subjected to rigorous in-house validation exercises using calibration blocks, culminating with an eventual field trial to confirm results.

A summary of the advantages of the re-developed disk bore region PAUT protocol includes:

- 100 percent coverage with overlap/redundancy in high-stress regions
- Custom primary probes with larger near-fields, increasing coverage and reducing risk of attenuation losses
- Three wedges per location; cut to specific radii to optimize component contact
- A flat wedge to establish ID roll to

determine coverage and to identify laminations in the part

- Pre-determined squint-angle wedges to optimize the reflective signals looking clockwise and counter-clockwise
- Contingencies in place to address attenuation and geometric variation risks

Detailed post-processing procedures have been established for the automated PAUT data to further aid in the detection of service damage resulting from IGSCC. To date, this redeveloped inspection protocol has been successfully used to inspect three Siemens 13.9 m² rotors at two nuclear facilities for two separate utilities.

SUMMARY

SIA provides comprehensive NDE and engineering assessments for the Siemens 13.9 m² DFLP rotor, including a recently validated, redeveloped PAUT protocol. This rotor's disk bore/keyway regions have historically faced IGSCC risk and challenging inspection geometry. To address this, SIA led a collaborative internal effort — bringing together Engineers, senior NDE technicians, and Applications Development support — to reinvent the inspection approach from the ground up.

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FIGURE 5. cleaned up graphic of Figure 4 highlighting coverage and overlap

The result is a new automated PAUT protocol that delivers 100 percent disk bore coverage with overlap and redundancy in high-stress areas, using optimized probe/wedge placements and validated focal laws. The protocol was modeled, simulated, and trialed in the field within a predictable, approximately five-day, two-shift outage window, and supports a defensible basis for rotor life assessments without de-stacking.

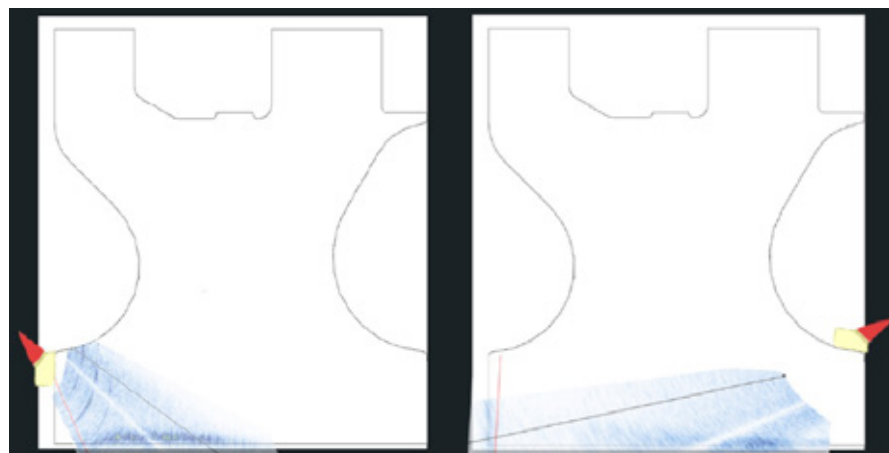


FIGURE 6. Screen shots of actual data with disk overlay showing coverage

DAY 1	DAY 2	DAY 3	DAY 4	DAY 5		
Setup, VT & Gauss Survey	Rotor WFMT	L-1 Blade PAUT & ET	Disk Bore	Disk Bore	Pack / Decon	Day Shift
Rotor WFMT	L-0, L-1 & L-2 PAUT	Disk Bore	Disk Bore	Analysis & Site Reporting	Nights Transition	Night Shift

Typical Rotor Inspection Schedule - 10 Shifts

FIGURE 7. Typical inspection schedule

SIEMENS 13.9M² OFFERING – A HOLISTIC APPROACH

Structural Integrity Associates provides comprehensive, fully integrated solutions for life assessment, inspection, failure analysis, and online monitoring of gas turbines, steam turbines, and generator equipment. Their holistic approach ranges from proactive management plans to emergent analysis and inspections. They offer unprecedented value by maximizing the life of existing assets in a safe, risk-informed manner.

NON-DESTRUCTIVE EVALUATION

For the 13.9m² DFLP rotor as a whole, the following nondestructive examinations are recommended to ensure appropriate coverage of the rotor periphery, L-0 blade roots, disk rim blade attachments, and shrunk-on disk-bores/keyways:

- Visual examination of the entire rotor periphery
- Wet fluorescent magnetic particle testing (WFMT) examination of the rotor steam path (L-0 through L-2 blades) and foil-hardened wear surfaces (L-0 blades)
- Manual phased array ultrasonic (PAUT) examination of the curved axial-entry L-0 stage blade roots
- Automated PAUT examination of the shrunk-on disk-bores/keyways for all three disks on both ends of the rotor
- Automated PAUT examination of the L-0, L-1, and L-2 stage axial entry disk rim blade attachments

With a six-person, two-shift crew, the complete NDE protocol—including setup, inspection, and data analysis—can be completed in approximately 10 shifts (five calendar days), minimizing outage duration and avoiding the added cost of de-blading.

ENGINEERING ASSESSMENT

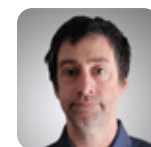
When indications are identified via NDE, the remaining service life of the rotor can be assessed using deterministic and probabilistic fracture mechanics to determine the likelihood of failure within a given operational envelope. Engineering analyses are used to assess life-limiting conditions, such as susceptibility and failure-consequence factors, and future operating expectations to derive a suitable inspection plan.

Learn more about SIA’s extensive expertise and experience with rotor inspections. Visit our website or contact us today.



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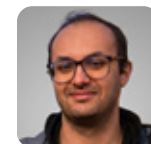
Leak-Before-Break and Flaw Tolerance for Advanced Reactors Under RIM Strategy



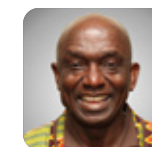
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EXECUTIVE SUMMARY

Advanced nuclear reactors, including small modular reactors, microreactors, and Generation IV concepts, are receiving significant attention as demand for clean, reliable, high-capacity power generation grows. Many of these designs are progressing rapidly through development, supported by evolving industry standards and upcoming U.S. Department of Energy (DOE) pilot programs. Their use of innovative materials, fabrication techniques, and operating environments underscores the importance of robust, technically grounded methods for demonstrating structural reliability and regulatory readiness.

The ASME Boiler and Pressure Vessel Code (BPVC) Section XI, Division 2 provides a comprehensive Reliability and Integrity Management (RIM) framework for advanced reactors.

Within this framework, deterministic and probabilistic fracture mechanics play a central role in confirming that passive components meet their reliability target throughout their operating life. Flaw tolerance analysis evaluates how flaws initiate and propagate under expected conditions, while Leak-Before-Break (LBB) assessments verify that any through-wall flaw will result in a detectable, stable leak before rupture. Together, these methodologies inform key design decisions, establish appropriate inspection and monitoring strategies, and support alignment with the U.S. Nuclear Regulatory Commission (NRC)-endorsed risk-informed, performance-based principles.

Structural Integrity Associates (SIA) has long-standing expertise in applying both deterministic and probabilistic fracture mechanics to support reactor designs across the

nuclear industry. Toolsets, including extended capabilities of SIA’s software, beyond-PRAISE™ and PROMISE, provide advanced modeling of fatigue, creep, and other high-temperature degradation mechanisms relevant to emerging reactor concepts. SIA’s active engagement in ASME Code development ensures that its methods reflect the latest industry and regulatory expectations. Combined with multidisciplinary in-house expertise in materials, Non-destructive evaluation (NDE), monitoring, and regulatory interpretation, SI provides a fully integrated approach that strengthens design confidence and supports efficient progression toward licensing and deployment.

BACKGROUND

With increasing demand for low-carbon power, driven in part by the rapid development of Artificial Intelligence

and data centers, nuclear power has experienced renewed interest over the last few years, especially in advanced reactors. Advanced reactors are next-generation reactors that go beyond conventional light-water reactors (LWRs). They include designs such as small modular reactors (SMRs), microreactors, and Generation IV reactors, as classified by the Generation IV International Forum (GIF). Many advanced reactors have moved beyond concept and are now in the design phase, with pilot programs supported by the DOE starting in early 2026.

Advanced reactors benefit from new technologies, such as 3D printing and new methods of monitoring. However, this is paired with a lack of experience and data with those technologies, which, over time, creates uncertainty about safety. Before entering service, the safe operation of each reactor must be demonstrated, and each reactor must be brought into compliance with the regulatory requirements set by the NRC. The task is made more complex by the fact that almost every new design is unique, making the review of each reactor less generic than for LWRs.

ASME BPVC Section XI Division 2 reliability and integrity management (RIM) is the response from ASME and the nuclear community to address some of those issues by proposing an approach that is built on a common methodology while remaining flexible for each individual case.

WHY IT MATTERS: ROLE OF FRACTURE MECHANICS UNDER RIM STRATEGY

RIM strategy is built on a risk-informed, performance-based framework that has been developed and refined over the years for LWRs. It relies, for instance, on probabilistic risk assessment (PRA) to evaluate the likelihood and potential consequences of accident scenarios. This strategy has been reviewed and is supported (with conditions) by the NRC as outlined in Regulatory Guide 1.246.

There are seven steps in the RIM process as shown in Figure 1.

One requirement of RIM (Step 4: “Identification and Evaluation of RIM Strategies”) is to demonstrate that passive components not covered by PRA operate as intended and meet their reliability targets. It is particularly important to demonstrate compliance with a robust methodology and appropriate design margins. This is especially critical when components are built with new materials (with limited testing), manufactured using new fabrication techniques, or subjected to new environmental conditions (e.g., use of a coolant other than water or operation at higher temperatures).

Leak-Before-Break (LBB) and flaw tolerance analyses are two of the major methods that can be used to ensure that the requirement is met using deterministic fracture mechanics (DFM) and probabilistic fracture mechanics (PFM). DFM evaluations can be performed with appropriate safety margins to meet or exceed the Component-Level Requirements (CLR) or demonstrate the CLR exceedance

is detectable before it reaches the postulated safety limit. On the other hand, PFM can be applied to ensure that the probability of failure is lower than the reliability target for any specific component. The outcome of these evaluations can provide guidance in

- Designing proper leak monitoring systems
- Redesigning piping loads
- Welding process and possible mitigation techniques
- Creep-fatigue monitoring system
- In-service inspection, etc.

HOW IT'S DONE: LBB AND FLAW TOLERANCE METHODOLOGIES

The LBB concept has been around since the early 1980s and is based on the statement that a stable leak from a small through-wall crack will be detectable before catastrophic rupture of a component, such as a pipe experiencing a double-ended guillotine break (DEGB). It stems from the principle that a small leakage would not jeopardize the component’s reliability. The leak detection would then allow the component to be repaired before a catastrophic failure.

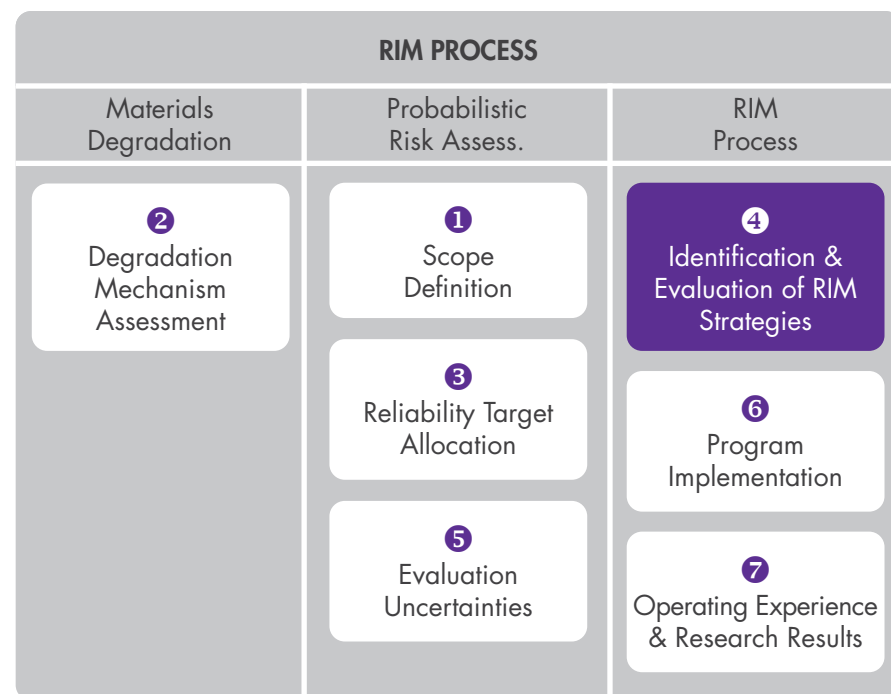


FIGURE 1. Steps in RIM Process

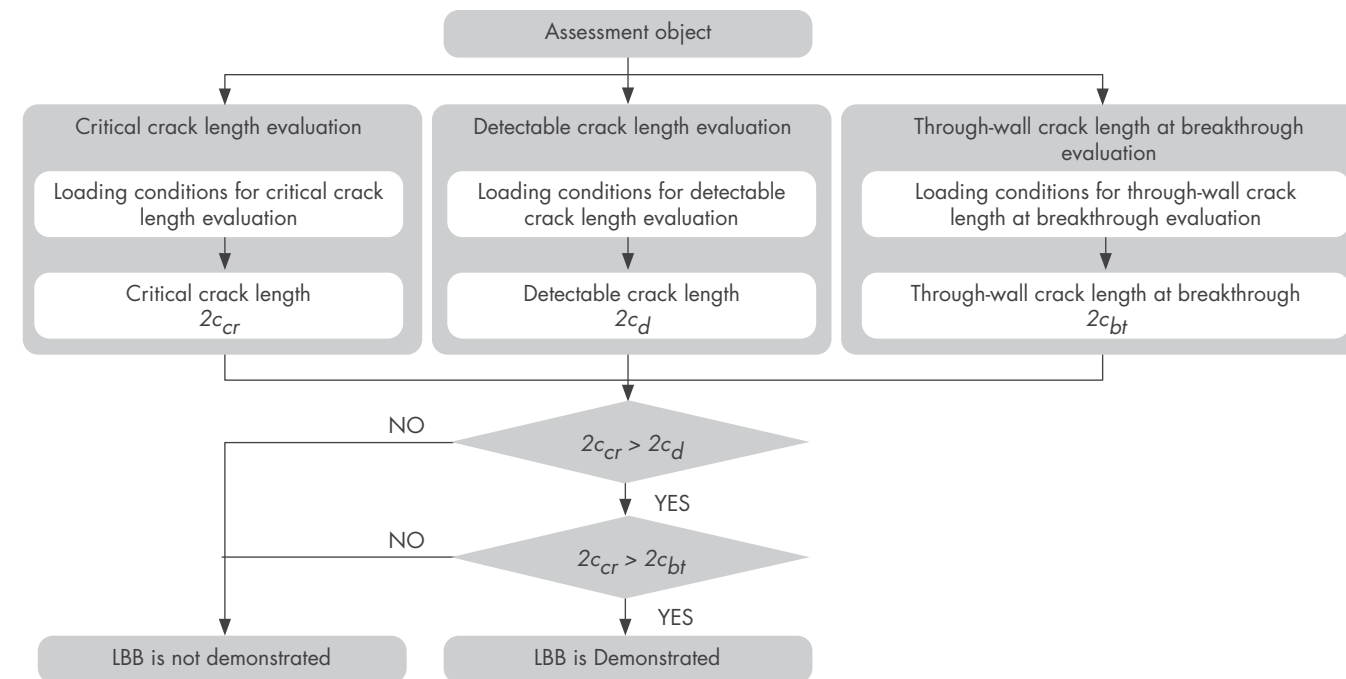


FIGURE 2. ASME Section XI div 2 LBB Assessment Flow

The procedure is presented in the Standard Review Plant (SRP) 3.6.3 (NRC NUREG-0800 “Leak-Before-Break Evaluation Procedures”) and has been used in support of meeting the General Design Criteria 4 (GDC-4) of 10CFR50 for LWR. The original method was deterministic and static, based on the ratio between critical crack length, which is the minimum length leading to pipe rupture, and the detectable crack length, which is the maximum length required to detect a leak rate. The methodology has evolved through time to capture the uncertainties via a probabilistic extension and to include a dynamic aspect, such as the estimation of the time between a detectable leak and a rupture.

The LBB procedure in RIM is similar to the one included in SRP 3.6.3 (as seen Figure 2), though it extends the applicability to axial cracks (SRP 3.6.3 was limited to circumferential cracks) and adds another layer for the defense-in-depth. This compares to the critical crack length with the through-wall crack length, which is the maximum crack length once a surface crack becomes through-wall.

Flaw tolerance analysis is a dynamic evaluation of a flaw’s evolution from nucleation to growth through the component. It estimates the potential loss of reliability (which could be due to leakage occurring or pipe rupture, for instance). It can be performed deterministically, often using conservative assumptions, to demonstrate reliability, or probabilistically to estimate the probability of loss of reliability. PFM and DFM are the main tools used to perform flaw tolerance analysis. A generic representation of PFM for flaw tolerance analysis is shown in Figure 3.

Advanced reactors feature different geometries, materials, and environmental conditions that affect the degradation mechanisms responsible for loss of reliability.

An example is the impact of creep, as many reactors operate at higher temperatures than LWRs, within the creep regime. Once the appropriate mechanisms and specific geometries are correctly identified and implemented, the flaw tolerance analysis is performed similarly to that for LWR.

The flaw tolerance and LBB evaluations are complementary and occur in series. While the flaw tolerance approach assumes the presence of a surface flaw and considers its growth to through-wall, the LBB approach assumes the presence of a through-wall flaw. As a result, the LBB evaluation begins where the flaw tolerance evaluation ends. With appropriate adaptations, the two methods can be applied to the unique characteristics of the structure, systems, or components (SSCs) in the advanced reactor. Their application during the design phase strengthens confidence in overall reliability and supports the evaluation of different designs, thereby reducing the cost of changes during pilot plant development.

STRUCTURAL INTEGRITY ASSOCIATES' EXPERIENCE

SIA has extensive experience performing LBB and flaw tolerance analyses using both deterministic and probabilistic fracture mechanics. SIA has a long history of developing customized PFM software, such as beyond-PRAISE and PROMISE, that has met the clients' needs while supporting a defensible regulatory strategy.

While the experience from previous analyses is invaluable, SIA understands the need to expand this knowledge to the current and future challenges associated with advanced reactors. One key point for applying LBB and flaw tolerance to advanced reactors is a good understanding of each reactor's specificities, potential new degradation mechanisms, and material properties.

By actively participating in ASME BPVC Code development focused on advanced reactors, SI staff is developing cutting-edge models consistent with ASME recommendations and has a better understanding of the regulatory concerns.

Additionally, SIA utilizes the Code platform to support approaches that are both applicable and approved by NRC and other regulatory entities.

SIA staff are actively involved in Section III Division 5 (construction of components for high temperature reactors), Section XI Division 1 (including the working group on high-temperature flaw evaluation), and Section XI Division 2 (RIM).

SIA also benefits from being a multi-disciplinary company that supports many aspects of the development and maintenance of nuclear power plants. Advanced reactors will depend on strong monitoring and non-destructive examination (MANDE), as shown in the MANDE part of the RIM program. Having in-house expertise in this area allows the analysts who are developing LBB and flaw tolerance code to better understand and represent those capabilities in their software, improving the overall quality of the analysis.

Structural Integrity Associates has been involved in supporting LBB and flaw tolerance evaluations for various piping systems and vessels of advanced reactors. The emphasis of that work is on methodology development and the key inputs (both deterministic and probabilistic) needed to perform the flaw tolerance evaluation. More important are discussions of the parameters that affect the evaluation's outcome, supported by sensitivity studies, which can provide valuable input for design modifications and component fabrication.

To perform these activities, SIA took the opportunity to expand the capabilities of its customized PFM software tool, PROMISE,

originally developed to optimize inspection schedules for various plant components. The PROMISE software derivative implemented a deterministic and probabilistic model of fatigue and creep-crack growth, consistent with the ASME Code, Section XI, Div. 2 and code case CC-934 methodology. SIA also has extensive experience in developing customized LBB software for LWRs and SMRs. This body of knowledge and expertise was used to expand PROMISE's capabilities to support advanced reactor applications.

BENEFITS FOR THE CLIENTS

A successful development of LBB and flaw tolerance analyses goes beyond the development of the codes themselves. Those analyses need to be integrated into a coherent approach that considers both upstream and downstream components.

- Downstream includes the development of models and the selection of appropriate inputs
- Upstream involves the interpretation and validation of the results and a comprehensive presentation that addresses potential regulatory concerns
- SIA supports clients across all aspects of integrated technical analysis. Drawing on its multidisciplinary team, SIA identifies and resolves gaps between the various elements of a global strategy, ensuring technical consistency and completeness. Depending on project needs, SIA can develop a comprehensive analytical framework, provide targeted technical guidance, or perform independent technical reviews.

Each analysis presents unique technical challenges that must be addressed systematically. With expertise in both probabilistic fracture mechanics (PFM) software development and the underlying physical principles, SIA develops and adapts analytical tools tailored to project-specific requirements.

Thanks to SIA's expertise and staff's involvement in ASME Code, SIA understands the regulatory requirements and can provide guidance on presenting and interpreting results in a clear, comprehensible way, reducing the risk of misinterpretation and potential delays in regulatory approval.

CONCLUSION

LBB and flaw tolerance evaluations are essential tools for ensuring the safe, reliable deployment of advanced reactor designs. With decades of proven experience developing and applying these methodologies, Structural Integrity Associates is uniquely positioned to support advanced reactor design. Our active role in shaping the ASME Code for advanced reactors aligns our approaches with the latest industry expectations and regulatory frameworks. By partnering with SIA, our clients tap into unmatched technical expertise and a strategic advantage that confidently brings their advanced reactor concepts to successful licensing and deployment.

Visit our website to see how Structural Integrity Associates engages with other elements of advanced reactor development, or contact us today.



structuralint.com/advanced-reactors

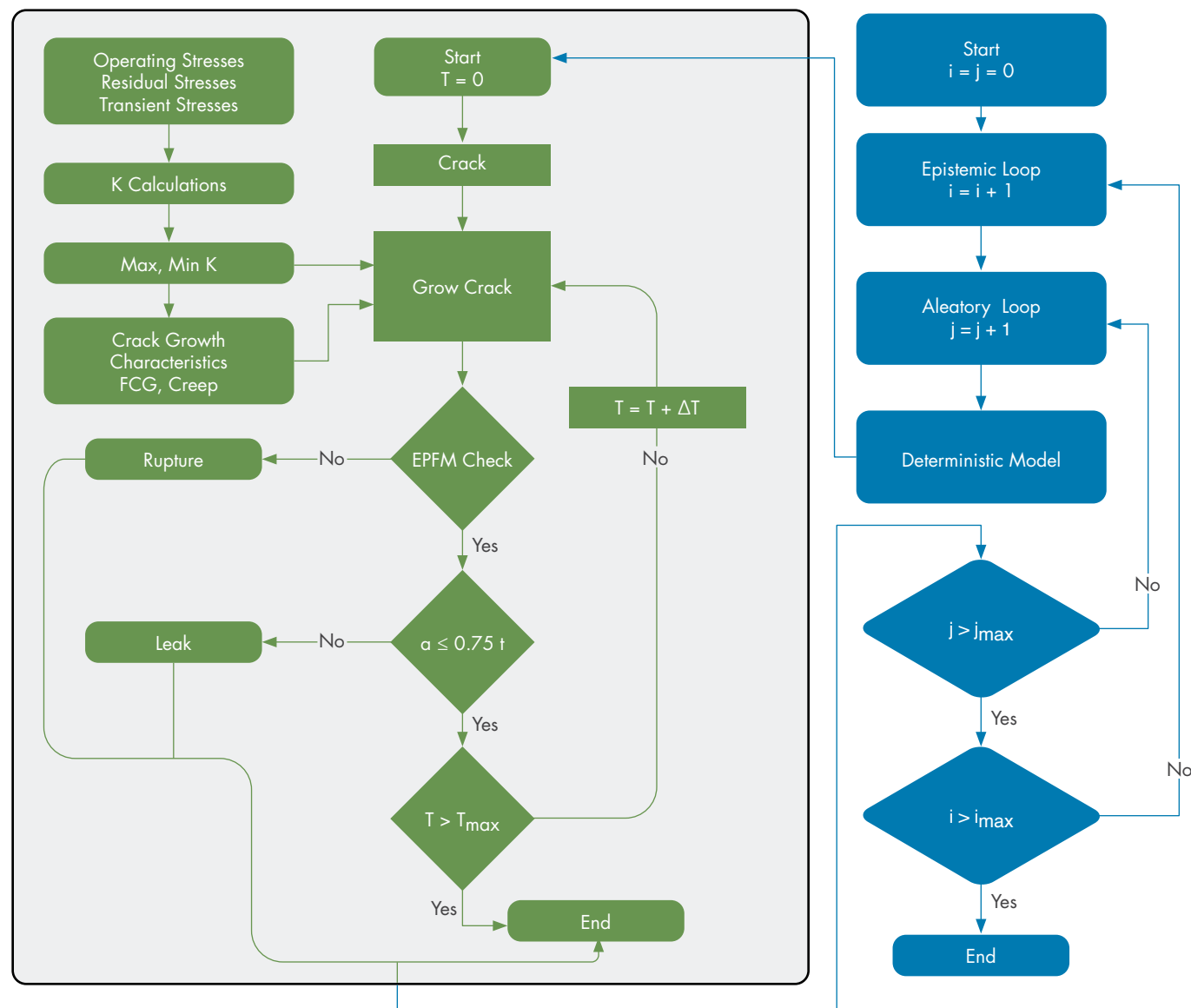


FIGURE 3. PFM overall technical approach for flaw tolerance analysis

From FEED to IFC: Delivering New-to-Site Process Technology on an Accelerated Schedule



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SEAMLESS ENGINEERING INTEGRATION POWERS A NEW PROCESS TECHNOLOGY

When a long-time chemical manufacturing client sought to expand production at its Houston, Texas chemical plant, they turned to C2C Technical Services (C2C) to engineer the initiative that represented more than a capacity increase—it introduced a new processing technology to the site. Successfully implementing that technology within an operating facility required thoughtful integration of existing assets, precise specification of new equipment, and close collaboration across engineering disciplines.

FROM FRONT END ENGINEERING DESIGN TO FULL MULTIDISCIPLINE EXECUTION

The project began with a front-end engineering design (FEED) study, establishing the technical basis for incorporating the new process into the existing plant infrastructure. Because the technology was new to the facility, the FEED phase focused heavily on process definition, equipment evaluation, and operability. This culminated in a ±10 percent total installed cost (TIC) estimate to support investment decisions.

Following FEED, the project advanced into full detailed design, delivering

construction-ready packages on an expedited timeline driven by business and market conditions.

INTRODUCING NEW TECHNOLOGY INTO AN EXISTING PLANT

The new process enables the blending of multiple liquid chemicals with powdered solids using an existing chemical reactor—an application not previously implemented at the site. Three raw materials and the finished product are stored in existing bulk tanks, requiring careful evaluation to confirm compatibility with new operating conditions.

Two newly specified pumps deliver liquid components to the reactor, where solid powder is introduced through a new material handling and conveying system. The reaction mixture is heated using the existing hot oil system via the reactor jacket, allowing the plant to leverage current utilities while supporting the new chemistry.

Upon completion of the reaction, the product is transferred through a newly installed pump to a new cooler, where temperature is controlled before entering a new static mixer. At this stage, an additional component is introduced to complete the formulation. The finished product is then routed

to existing product storage tanks and loaded into trucks using existing transfer systems.

This approach required C2C to maintain a careful balance of repurposing existing equipment—including pumps, an agitator, cooling tower capacity, and absorber systems—while specifying new equipment where performance, safety, or operability demanded it.

PRECISION DESIGN IN A LIVE OPERATING FACILITY

To support accurate design in congested plant areas, the C2C team performed 3D laser scanning of the reactor, tank farm, and pipe rack areas and built a comprehensive 3D engineering model of the facility. Leveraging this model, C2C designed and engineered the project's new piping, automated block valves, relief routing, nitrogen purging systems, and truck offloading facilities.

Instrumentation and electrical engineering were fully integrated into the design, with Emerson's DeltaV™ distributed control system (DCS) programming, graphics, alarms, interlocks, and shutdown logic developed alongside physical layouts. Electrical design included revised one-line diagrams, motor schematics,

grounding systems, lighting, and electrical heat tracing.

STRUCTURAL AND INFRASTRUCTURE ENHANCEMENTS

In addition to the process unit, the project included the design of a new elevated pipe rack structure, spanning approximately 250 feet between the plant and a neighboring terminal. Structural and civil design supported multiple process lines, automated valves, and future flexibility—all delivered as part of a single, coordinated engineering effort.

ONE INTEGRATED TEAM, ONE SUCCESSFUL OUTCOME

Throughout execution, C2C Technical Services operated as an integral extension of the client's engineering team, managing interfaces, maintaining

quality control, and delivering complete Issued-for-Construction (IFC) drawing packages that formed the basis for procurement and construction. Despite the accelerated schedule and the introduction of new-to-site technology, the project was delivered safely and efficiently.

OPERATIONAL, SAFE, AND READY FOR GROWTH

As of this publication, the unit is online and operating safely, enabling the client to expand production using a new processing technology while maximizing the value of existing infrastructure. The project stands as a clear example of how integrated teams, aligned cultures, and disciplined engineering can successfully introduce innovation into established industrial facilities.



COMPLEMENTARY STRENGTHS, NOW A UNIFIED ENGINEERING TEAM

Midway through the project, Flesch Engineering merged with C2C Technical Services, forming a more comprehensive engineering organization without disrupting progress. Flesch's strengths in process, piping, civil, structural, and mechanical design were complemented by C2C's deep expertise in instrumentation, electrical, and controls engineering.

The merger strengthened the project team at a critical moment, enhancing technical depth while maintaining continuity, schedule, and client confidence.

Equally important, both firms shared a common culture centered on technical rigor, collaboration, and long-term client relationships. As a result, the newly integrated team functioned seamlessly as an extension of the client's organization.

C2C Technical Services is more poised, now more than ever, to deliver complex projects with confidence, precision, and a strong commitment to client partnership.



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Modernization of a Legacy Cathodic Protection System for Subsequent License Renewal



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Learn how an existing, underperforming cathodic protection (CP) system was technically evaluated and modernized to meet current effectiveness expectations, without full replacement.

OVERCOMING A COMMON CHALLENGE

When planning for extended operation, many nuclear energy facilities face the common challenge of determining how best to address aging infrastructure, specifically whether to repair, augment, or fully replace existing systems. U.S. nuclear energy plants entering subsequent license renewal (SLR) with existing cathodic protection systems often must evaluate the original CP system design basis and related assumptions. Plant operators also assess the overall condition and capability of the existing system to ensure it meets current and future needs.

In 2024, Xcel Energy contracted with Structural Integrity Associates (SIA) to conduct a feasibility and design study for a cathodic protection system at the Monticello Nuclear Generating Plant (MNGP). Following the design study, SIA developed a detailed design basis for a supplemental CP system intended to meet the site's regulatory

commitments for SLR, supporting continued operations through September 8, 2050.

For sites such as Monticello with long-serving CP infrastructure, the appropriate path forward is site-specific and depends on multiple technical and regulatory factors, including:

- Age, condition, and demonstrated effectiveness of the existing CP system
- Required service life of the system to support extended operation
- The continued applicability of the original CP design basis
- Changes in plant configuration since the original system was installed
- Changes in the scope of systems, structures, and components requiring protection
- Evolution of regulatory guidance and aging management expectations

The details in this article demonstrate the evaluation, design, and implementation of a site-wide CP system upgrade at Monticello Nuclear Generating Plant, developed within this decision framework, to support effective aging management during the subsequent period of extended operation (SPEO).

EXISTING CATHODIC PROTECTION SYSTEM

Cathodic protection for buried piping and tanks was first introduced at MNGP as part of the original site design and construction in 1970. The original system included a combination of distributed impressed current cathodic protection (ICCP) and galvanic anode CP (GACP). This system was designed to protect key buried assets such as cooling water lines, radioactive waste piping, fuel tanks, and condensate tank bottoms. The system was not site-wide, nor was it intended to cover the specific buried piping and tanks now identified within the SLR scope.

Over time, reliability issues, depleted anodes, and site modifications necessitated the installation of a replacement ICCP system.

In 2010, a new sitewide ICCP system was installed, consisting of five rectifiers and semi-deep anode groundbeds. This system was designed with a total capacity of 150 amperes of direct current (ADC), but over time the individual circuit resistance of the groundbeds limited the actual output to approximately 95 ADC. Records indicate that additional semi-deep anode groundbeds were included in the design; however, they were never installed.

CP performance is monitored annually, and evaluations were expanded in 2021 to survey the entire facility. The 2021 survey showed that approximately 50 percent of monitored test points did not meet the required CP acceptance criteria. Adjustments to the rectifier outputs yielded limited improvements and indicated that the system, in its current form, was both undersized and provided inadequate current distribution. It was determined that

a significant CP system upgrade or replacement would be needed to increase available current and improve distribution. This would help to ensure the protection of all SLR in-scope buried piping and tanks.

ASSESSMENT METHODOLOGY

The feasibility and design study evaluated the condition, performance, and limitations of the existing CP system to determine whether refurbishment, augmentation, or full replacement would be required to support Monticello Nuclear Generating Plant's SLR commitments. A secondary objective was to assess whether a sitewide CP system would be practical given the plant's physical and operational constraints.

The evaluation drew on three primary workstreams: a review of historical documentation and operating data; targeted field testing and site walkdowns; and direct discussions with station personnel and contractors to characterize construction and installation constraints.

1. Review of Historical CP Surveys and Rectifier Data

Historical CP performance was assessed through annual survey data, rectifier operating records, and supporting documentation spanning decades of system operation. Particular emphasis was placed on the expanded survey efforts conducted between 2021 and 2024. Those results consistently showed that a significant portion of monitored test points failed to meet the -850-mV copper sulfate electrode (CSE) polarized potential criterion specified by applicable U.S. NRC guidance, with approximately half of all monitored locations remaining underprotected even at maximum rectifier output. This pattern indicated a systemic limitation rather than localized piping issues, such as isolated coating defects.

Rectifier operating data told a similar story. The five existing rectifiers were originally designed for a combined output of approximately 150 ADC, but, at the time of the study, measured circuit resistances constrained the

CONTINUED...



FIGURE 1. Cathodic Protection System Overview

practical output to 90–100ADC under normal operating conditions. Incremental voltage increases produced diminishing returns, confirming that circuit resistance and current distribution, not rectifier capacity alone, were limiting the system's effectiveness. The rectifiers and above-ground components, such as anode junction boxes, were found to be in generally good condition, with no near-term concerns regarding their remaining service life. The anode groundbeds, however, showed varying degrees of degradation and would likely require replacement before the end of the SPEO, consistent with their original design intent.

2. Identification of System Deficiencies

Correlating the survey results, rectifier operating limits, and site configuration constraints revealed several compounding deficiencies: insufficient total current capacity relative to the expanded SLR scope; poor current distribution to congested areas; and limited ability to mitigate shielding and attenuation effects caused by buried plant infrastructure and grounding systems. The assessment also found that the legacy CP system design basis was no longer aligned with current regulatory expectations or the buried piping scope required for the full SLR interval. Based on these findings, refurbishment of the existing system alone was deemed insufficient.

3. On-Site Testing and Walkdowns

To validate design assumptions and characterize current site conditions, SIA conducted on-site testing focused on two critical variables: electrical continuity of buried piping systems and soil conditions across the facility. Soil resistivity testing revealed significant spatial and depth-dependent variability, with shallow soils ranging from approximately 1,900 Ω-cm to greater than 76,000 Ω-cm, a range that directly influenced assumptions about required current capacity, anode configuration, and rectifier specifications.

Site walkdowns and discussions with station personnel identified the constructability constraints that any new CP infrastructure would need to navigate, including dense buried utilities, plant grounding systems, structural foundations, and Protected Area limitations. SIA used these findings to develop a preliminary sitewide system design and to validate its potential feasibility against logistical challenges. While the preliminary design required several revisions, key stakeholders ultimately concluded that a sitewide CP system was both feasible and capable of delivering effective long-term protection.

4. Upgrade Versus Replacement Considerations

Evaluation of the existing CP system weighed full replacement against targeted augmentation of legacy infrastructure, considering site constructability constraints, anticipated performance improvements, and long-term operation and maintenance factors.

Full replacement would have required removal or abandonment of existing anode groundbeds, cabling, and rectifiers, all of which had years of serviceable life remaining. This would also increase construction complexity, particularly within the Protected Area. Augmentation avoided or delayed those costs and complications by reusing serviceable components and minimizing the near-term excavation scope.

Historical performance evaluations reinforced this direction. The identified deficiencies were driven primarily by insufficient current capacity and poor current distribution, rather than by widespread component failure, meaning that targeted augmentation offered a clear path to compliance with applicable CP acceptance criteria by supplementing the existing CP infrastructure.

A hybrid design incorporating continued use of existing groundbeds alongside supplemental anode capacity was therefore identified as both technically justified and the most cost-effective path forward.

SELECTED UPGRADE STRATEGY

The selected strategy retained the existing five ICCP anode groundbeds and rectifiers while adding two forms of supplemental capacity. First, one additional semi-deep remote anode groundbed, similar in construction and capacity to those already in service, was specified to improve system balance and optimization. This was particularly true for buried piping near the cooling tower, where under- and over-protection had been recurring concerns. Leveraging the existing design for this addition minimized engineering change effort and allowed the substantial operational data from existing installations to inform the new semi-deepwell design.

Second, six distributed anode groundbeds were added in proximity to in-scope piping to address current distribution deficiencies more directly inside the PA. Each distributed groundbed included 12 shallow vertical anodes spaced approximately 10 to 20 feet from target pipelines on approximately 25 to 35-foot centers. Finally, dedicated CP test stations were installed throughout the plant to improve the accuracy and efficiency of future effectiveness testing.

Under the Subsequent License Renewal (SLR) framework defined in 10 CFR Part 54, nuclear plant licensees must demonstrate that aging effects on in-scope structures, systems, and components will be adequately managed throughout the extended 60-to-80-year operating period. The Generic Aging Lessons Learned for Subsequent License Renewal (GALL-SLR) report identifies buried metallic piping and tanks as systems requiring active aging management.[2]

Cathodic protection systems are therefore an important corrosion mitigation measure for maintaining the integrity of buried piping systems and storage tanks throughout extended plant operation.

CP SYSTEM DESIGN BASIS AND APPROACH

The cathodic protection (CP) system upgrade was developed to address performance limitations identified during the system assessment and to support long-term operation under the Subsequent License Renewal. Design criteria were established in accordance with AMPP/NACE SP0169 and applicable NRC guidance for buried piping and tanks. The primary protection criterion was defined as a polarized potential of –850 mV CSE (instant-off) for buried carbon steel, with provisions for applying alternative criteria when justified by environmental conditions or verified corrosion rates. [2] [3]

Design assumptions incorporated the expectation that most buried metallic piping systems are electrically continuous, either by original design intent or through incidental bonding to the station grounding grid. Historical continuity testing supported this assumption and the

system configuration allows for future identification and mitigation of localized discontinuities.

Site-specific constraints played a significant role in shaping the final design. Soil resistivity testing demonstrated substantial spatial variability, and shallow bedrock limited the feasible depth of remote anode installations from approximately 60-80 ft. In addition, the plant's Protected Area contains extensive buried utilities, grounding systems, and structural foundations that influence current distribution and restrict potential installation locations. These conditions were incorporated directly into the CP system design basis.

Key Site Constraints

- Geological constraints related to shallow bedrock that limit remote deep anode well depths
- Highly variable soil resistivity across the site
- Localized high-resistivity zones at shallow depths
- Physical congestion within the Protected Area, restricting construction access and anode placement
- Extensive buried and above-grade metallic infrastructure that can influence current distribution and create shielding effects

To address these challenges, the upgraded CP system integrates existing infrastructure with supplemental anode capacity. Existing semi-deep anode groundbeds and rectifiers were retained based on their demonstrated serviceability and remaining operational life. These groundbeds continue to provide baseline current output and broad site coverage.

Supplemental distributed shallow anode groundbeds were installed at targeted locations to improve current distribution and provide localized protection for piping segments that were historically difficult to polarize.

Positioning these anodes closer to protected structures reduces shielding effects from plant infrastructure and lowers the effective circuit resistance.

The resulting system reflects a hybrid current delivery strategy, combining centralized, semi-deep groundbeds with distributed shallow anodes. The rectifier distribution and circuit configuration were developed based on geographic grouping of piping systems, anticipated current demand, and constructability considerations. This configuration allows the CP system to operate as a coordinated network while enabling individual zones of influence to be balanced and adjusted during routine system maintenance.

Rectifiers were specified with sufficient voltage margin to accommodate variability in soil resistivity and circuit resistance.

The upgraded design also incorporates remote monitoring units (RMUs) installed on each rectifier. These units provide high-frequency monitoring of rectifier outputs and operating status, with data transmitted directly to the site's MAPPro™ database for centralized access.

Remote monitoring improves visibility into system performance, supports early identification of equipment issues, and enables remote interruption of rectifiers during future effectiveness surveys.

CONTINUED...



FIGURE 2. Installed rectifiers

INSTALLATION, COMMISSIONING, AND PERFORMANCE

Construction of the supplemental CP system was completed by Xcel Energy contractors, with Structural Integrity Associates providing on-site engineering oversight. Installation was completed as planned, including one semi-deep remote anode groundbed and six distributed groundbeds totaling 72 shallow anodes. Following installation, SIA performed system energization and current balancing in accordance with the site commissioning procedure developed by SIA for the project. System performance was evaluated through the annual CP effectiveness survey conducted following commissioning. The survey was performed in accordance with established site procedures and industry guidance, with nearly 70 structure-to-soil potentials measured and evaluated against the -850 mV CSE instant-off protection criterion.

Survey results demonstrated a substantial improvement in CP effectiveness compared to pre-upgrade conditions. Before system rehabilitation, approximately 50 percent of monitored test locations met the required protection criterion. Following installation and system balancing, more than 85 percent of surveyed locations met the applicable protection criteria, with additional adjustments planned to further improve overall coverage.

Survey coverage was also expanded relative to historical testing by adding new CP test stations installed as part of the upgrade project. The increased monitoring resolution provided improved visibility into localized system performance. It confirmed that the upgraded system configuration largely mitigated the current distribution limitations identified during the assessment phase.

Post-installation rectifier operating data also indicated that sufficient

voltage and current capacity remain available across the system. This operating margin provides flexibility to accommodate potential future changes in site conditions, including coating degradation, expansion of buried piping scope, or evolving regulatory expectations, without requiring major system modifications. The available adjustment capacity also allows incremental tuning of individual rectifiers and groundbeds during routine CP maintenance and annual effectiveness surveys, consistent with NACE SP0169 guidance. [3]

While overall system performance improved significantly, the post-installation survey identified several localized areas where additional optimization may further enhance protection. Planned follow-up actions include targeted system balancing, installation of additional electrical continuity bonds where necessary, selective corrosion rate monitoring, and potential installation of a limited number of additional anodes with the goal of achieving sufficient external corrosion protection on 100% of the sites in-scope buried piping and tanks.

Long-term system management will also include monitoring the remaining life of the existing semi-deep anode groundbeds. Although these groundbeds remain serviceable, not all are expected to remain functional through the end of the subsequent period of extended operation (SPEO) in 2050. Replacement of individual anode beds will be performed as needed to maintain full system effectiveness while supporting long-term use of the legacy rectifiers. The implementation of remote

monitoring units will assist in tracking rectifier performance and identifying potential anode depletion, enabling timely maintenance and replacement.

LESSONS LEARNED

Key lessons from the Monticello CP system upgrade include:

- Site geology strongly influences CP design feasibility. Shallow bedrock and highly variable soil resistivity required careful evaluation of anode placement and current distribution strategies.
- A hybrid ICCP configuration can effectively balance system performance and constructability. The combination of semi-deep remote groundbeds and distributed shallow anodes provided both bulk current capacity and targeted protection in congested areas.
- Localized shielding near large structures remains a challenge. Buried piping near building foundations and structural infrastructure can be more difficult to polarize despite otherwise successful system performance.
- Early planning is essential for SLR-related CP upgrades. Evaluation of legacy CP systems should begin well in advance of regulatory deadlines to allow sufficient time for assessment, design iteration, installation, and post-installation optimization.
- Allow schedule flexibility for equipment procurement and system tuning. Rectifier sizing and installation occurred concurrently with construction due to long equipment lead times and uncertainty about highly variable soil resistivity.

SUMMARY

The Monticello project illustrates how legacy corrosion mitigation infrastructure can be strategically upgraded to meet the industry's evolving regulatory and operational expectations for subsequent license renewal. By combining historical evaluation, targeted field testing, and practical design solutions, SIA developed an upgrade strategy that improved protection coverage while minimizing construction impacts and preserving serviceable existing infrastructure.

As buried infrastructure ages and the SLR scope expands, utilities across the nuclear industry face mounting pressure to demonstrate that legacy CP systems can meet modern regulatory expectations. SIA's corrosion engineering specialists bring extensive experience in assessing, designing, and implementing cathodic protection systems for complex facilities. Through projects such as Monticello, SIA helps utilities develop technically defensible, cost-effective solutions that support long-term asset reliability and regulatory compliance.

To learn more about Structural Integrity Associates' cathodic protection expertise and other advanced engineering services supporting extended plant operation, contact us or visit www.structint.com.

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Materials Lab Featured Damage Mechanism

Stress Corrosion Cracking in Boiler and HRSG Tubes



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Stress corrosion cracking (SCC) is an environmentally-assisted form of damage that occurs when a susceptible tube material is exposed to a contaminant that concentrates in an area affected by tensile stresses in excess of a threshold value; typically, well below the material's yield strength. This damage mechanism is most frequently associated with austenitic stainless steel tubing, but it can also affect carbon and low-alloy steels. Crack growth rates can be especially rapid, depending on the specific conditions of interaction between the material and the environment. Propagation can be intergranular, transgranular, or a mixture of both. Stress corrosion cracking can be a particularly insidious form of damage because once the first leak is discovered, many tubes typically will have suffered some level of damage.

MECHANISM

Despite extensive research into how stress corrosion cracks initiate and grow, no consensus on the mechanism has been achieved. In fact, there is compelling evidence that SCC may initiate and grow by more than one mechanism, depending on the material involved and the specific environmental factors that exist when the cracking occurs. These factors include the type of contaminant, the concentration of

the contaminant, the local temperature, and the level of stress. The common feature of all of the proposed mechanisms is the required interaction between a specific contaminant and a location on the material subjected to a critical level of tensile stress. In the absence of the susceptible material, contaminant, or the stress, cracking will not develop.

Materials that form robust passive films in air and are resistant to general corrosion, such as the austenitic stainless steels, tend to show greater susceptibility to stress corrosion cracking. Cracking can be transgranular (through grain), intergranular (along grain boundaries), or mixed transgranular/intergranular. Intergranular stress corrosion cracking in sensitized austenitic stainless steels is typically caused by exposure to sulfates or sulfur-based contaminants. Transgranular stress corrosion cracking in stainless steels is most often caused by exposure to a chloride contaminant.

TYPICAL LOCATIONS

SCC can occur anywhere there is a source of tensile stress and the possibility for concentration of a contaminant. Such cracking can initiate on either the outer or inner diameter surface of the tubing. In

superheater and reheater tubing, these two requirements most often are met at locations such as cold-formed bends, particularly the lower bends of assemblies where condensate collects, in welded attachments of straight tubing, and in butt welds. For any of these locations, if the austenitic stainless tubing has been properly annealed or if the ferritic tubing has received an appropriate stress-relieving heat treatment, SCC typically will not occur. This is because the tensile stress component of the damage mechanism is insufficient to initiate damage.

SCC failures have also been reported in HRSGs and are typically associated with the colder gas-path circuits nearest the stack. These included the last—or last few—heat transfer surfaces before the stack, such as low-pressure economizers and preheaters.

FEATURES

- Stress corrosion cracking failures typically are thick-edged, brittle failures that may involve the blowout of window-type pieces.
- The cracks can be circumferential or longitudinal and frequently have significant branching, particularly at the microscopic level.



FIGURE 1. Circumferential stress corrosion cracking (SCC) in a stainless steel reheat tube on the OD (left) and ID (right)



FIGURE 2. Longitudinal SCC in a stainless steel low-temperature superheater tube

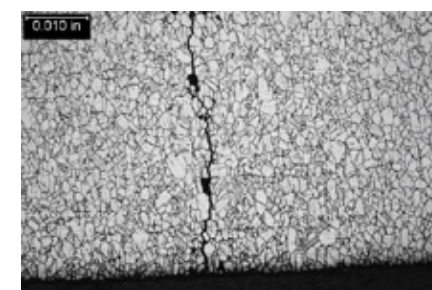


FIGURE 3. Intergranular stress corrosion cracks in a stainless steel reheater tube, OD initiation



FIGURE 4. Longitudinal SCC in a carbon steel high pressure econ tube on the OD (left) and ID (right)

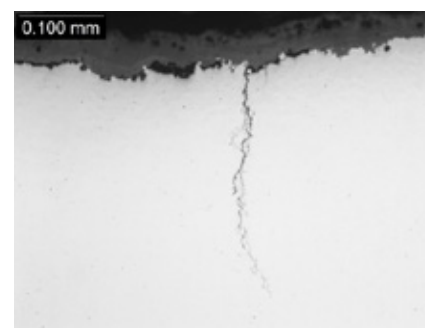
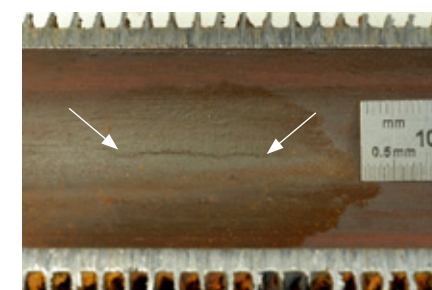
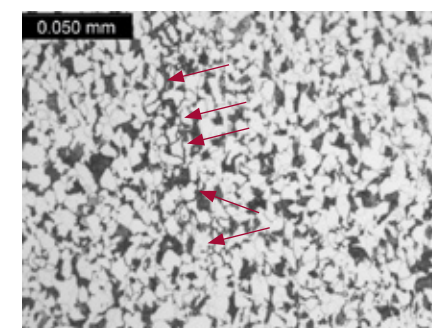


FIGURE 5. Intergranular stress corrosion cracks in a carbon steel HP Econ tube, OD initiation



ROOT CAUSES

Stress corrosion cracking will occur when a susceptible material is exposed to a specific contaminant and a critical level of tensile stress. The stress can be residual and/or applied. Residual stresses often are related to welding or cold-forming. Also, applied stresses are associated with either normal or abnormal operation of the component. Since relatively high levels of tensile stress exist at many different boiler tube locations (e.g., as-welded tube butt joints) during normal boiler operation, an investigation into the cause of SCC often focuses on identifying and eliminating the responsible contaminant. For cracking that initiates on the steam-side of the tubing, potential sources of contaminants include:

- Carryover of chemicals from a chemical cleaning operation
- Carryover of boiler water from the steam drum
- Introduction of contaminated attemperator spray
- Ingress of fireside contaminants into a primary failure where a vacuum has been created by the failure

For cracking that initiates on the external surface of the tubing, obvious sources of contamination are the ash and flue gas.

When ongoing failure risk is unacceptable, an accurate assessment is critical — SIA's Metallurgical Laboratory can deliver exactly that, from identifying damage mechanisms and root causes to delivering actionable recommendations on serviceability, material selection, and failure avoidance. Backed by SIA's integrated expertise in stress analysis, modeling, and nondestructive testing, our team goes beyond lab results to provide engineering solutions tailored to your operation. To explore our capabilities or submit a sample, visit structint.com/metallurgical-laboratory.



Engineering Critical Assessment of Lap Welds

A Specialized ECA Framework for Lap Weld Pipeline Infrastructure



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Pacific Gas and Electric Company (PG&E) and Structural Integrity Associates (SIA) have developed and deployed a first-of-its-kind Engineering Critical Assessment (ECA) process for lap-welded pipe — providing a cost-effective, regulatory-compliant alternative to full pipe replacement.

WHAT IS AN ENGINEERING CRITICAL ASSESSMENT (ECA)?
 An Engineering Critical Assessment is a fracture-mechanics-based analytical methodology that allows pipeline operators to confirm the safe and reliable operation of critical assets.

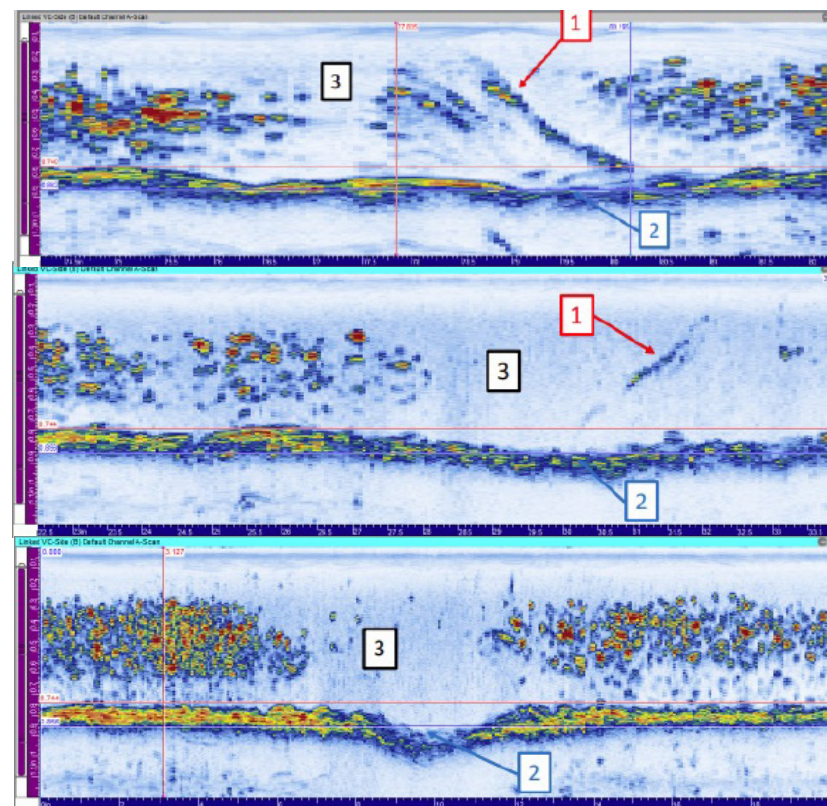


FIGURE 1. PAUT scans at 0° incidence (image is analogous to a cross-section of the weld) from hammer-welded pipe showing seam indications (1), increased wall thickness at the seam (2), and clean areas adjacent to the seam (3). The upper two images show bond line indications consistent with lack-of-fusion; the lower image shows no bond line indications."

Recognized under 49 CFR Part 192, ECAs are a regulatory-approved method for Maximum Allowable Operating Pressure Reconfirmation (MAOPR) of onshore steel transmission pipelines.

Fundamentally, ECA entails completing a comprehensive assessment that will identify and evaluate applicable threats and confirm that no unacceptable flaws exist that will lead to failure. The process involves performing an engineering analysis as part of the assessment to determine the maximum tolerable flaw size a pipeline can sustain while continuing to operate safely. This involves rigorous consideration of:

- Material properties and operating history
- In-service degradation mechanisms and failure modes
- Advanced non-destructive examination (NDE) results
- Fracture mechanics modelling and failure pressure predictions

LAP-WELDED PIPE, A UNIQUE CHALLENGE

Lap-welded pipe — manufactured primarily in the 1920s using a forge-welding technique — presents unique integrity challenges. While largely supplanted by other pipe manufacturing techniques by the 1940s, segments of lap-welded pipe remain embedded in gas transmission and distribution facility piping across the U.S.

Manufacturing Process and Inherent Flaws

The lap-welding process involved heating steel skelp to extreme temperatures and pressing overlapping scarfed edges together using heavy rolls and a mandrel. The process relied on inconsistent, low quality welding processes using lower-grade Bessemer steel combined with elevated sulfur content — conditions that gave rise to inherent defects, including:

- Hot Shortness: sulfur-induced embrittlement and cracking at the weld interface (Figure 1)

- Burning: grain-boundary sulfide formation causing cracking upon cooling
- Oxide Entrapment: lack-of-fusion areas caused by surface oxidation during underheating (Figure 2)

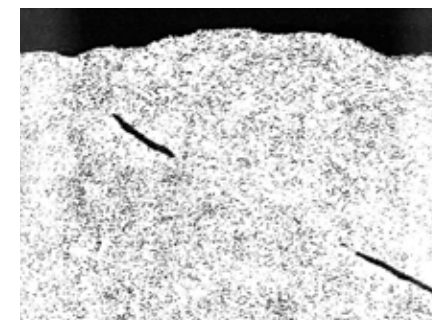


FIGURE 2. Lap-welded pipe showing entrapped oxide at the bond line¹

These defects manifest as lack-of-fusion indications detectable via ultrasonic testing — making advanced NDE techniques the cornerstone of the ECA approach for lap-welded pipe.

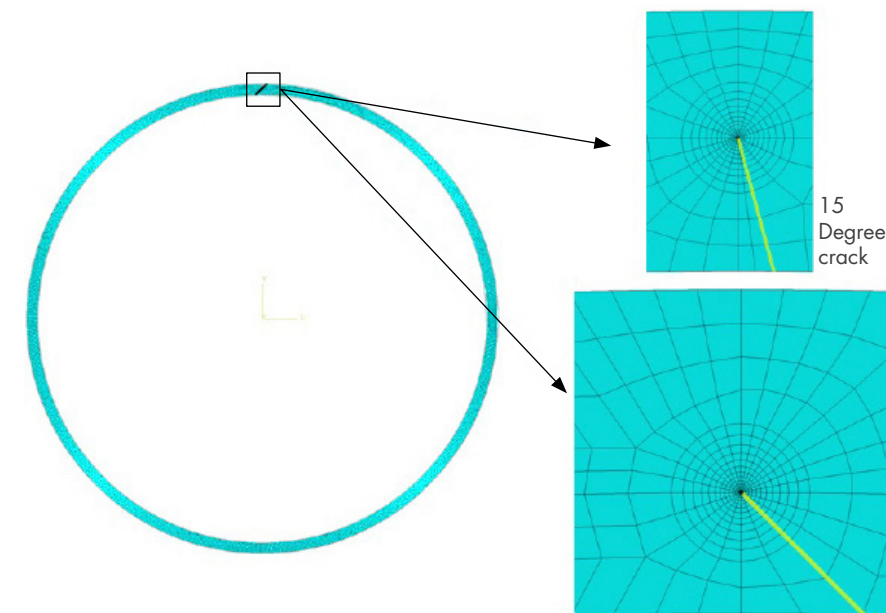


FIGURE 3. Lap-welded pipe example FEA simulation.

ECA METHODOLOGY DEVELOPMENT

SIA worked with PG&E to develop a comprehensive, multi-phase ECA methodology tailored specifically to assess lap-welded pipe by integrating fracture mechanics analysis with a customized NDE inspection protocol to help augment their facility ECA program.

Fracture Mechanics and Defect Acceptance Criteria

Critical flaw curves were developed using SIA's APTITUDE™ fracture mechanics software, applying an API 579 Level 2 Failure Assessment Diagram (FAD) approach. Flaws are evaluated against two acceptance criteria:

- Flaw height exceeding 50% of wall thickness (per RIN 2 pipeline safety regulation)
- Predicted Failure Pressure (PFP) below 1.25x MAOP for shallower flaws

A finite element model (FEM) built in Abaqus validated the analytical approach, confirming that APTITUDE provides conservative yet accurate stress intensity calculations across a range of weld angles (Figure 3).

CONTINUED...

Lap Weld NDE Development

To evaluate the NDE process, SIA gathered key information regarding potential defect types, weld configuration and properties, and flaw characteristics. SIA performed advanced modeling of the ultrasonic wave propagation to optimize the approach for detecting the required flaws. The NDE approach was then evaluated and refined in the lab on cut-out sections of lap weld pipe donated by PG&E. Based on the modeling and lab testing, a Scan Plan as part of a detailed NDE Inspection Protocol was developed. The protocol included the use of MPI, shear wave PAUT, and zero-degree PAUT to ensure full coverage of the seam for all identified defect types.

Advanced NDE Inspection Protocol

A four-step field inspection protocol was developed and validated on laboratory specimens before pilot deployment:

1. Identify lap-welded pipe via characteristic 'spellerizing' surface patterns and ultrasonic confirmation.
2. Locate the lap-welded seam using circumferential grinding/polishing/etching, visual examination, and phased array ultrasonic scanning.
3. Execute Magnetic Particle Inspection (MPI) for surface-breaking defects, followed by encoded Phased Array Ultrasonic Testing (PAUT) following a defined ECA protocol.
4. Evaluate all identified indications against ECA-derived acceptance criteria.

FIELD TESTING RESULTS

The methodology was successfully deployed at two PG&E gas transmission and distribution facilities; Figure 4 illustrates a representative example of the in-scope piping. The pilot confirmed the practicality and effectiveness of the approach:

- While some mid-wall indications were detected during inspection, none of the identified indications

- exceeded 30% of wall thickness — well below the 50% acceptance threshold
- All subject piping was confirmed fit for continued safe operation

The pilot demonstrated that a rigorous, targeted ECA process can provide operators with a defensible, cost-effective alternative to pipe replacement or hydrostatic retesting for legacy lap-welded assets.

KEY TAKEAWAYS

SIA has worked with PG&E to help successfully apply the ECA process for facility piping to support MAOP Reconfirmation. Certain defects and piping configurations pose significant challenges to conventional techniques. Lap-welded pipe represents one of the more challenging integrity management problems facing gas utility operators today and is difficult to assess using conventional NDE techniques. This work establishes a repeatable, regulatory-supported framework that:

- Leverages advanced modeling and NDE to assess lap weld pipe defects
- Reduces unnecessary pipe replacement through evidence-based fitness-for-service evaluation

References

^[1] J.F. Kiefner and E.B. Clark, CRTD-Vol. 43 History of Line Pipe Manufacturing in North America, New York: ASME, 1996.

- Supports MAOP reconfirmation obligations under 49 CFR Part 192
- Provides a documented, defensible record for regulators and stakeholders

This collaboration with PG&E demonstrates that a rigorous, first-of-its-kind ECA methodology can be successfully developed and deployed to address legacy infrastructure that conventional methods cannot adequately assess. For more information on SIA's pipeline integrity services and capabilities, visit www.structint.com/pipeline-integrity



FIGURE 4. Example of facility piping with lap weld inspection applied.

Using AI to Unlock Asset Integrity Data

Without Sacrificing Safety, Accuracy, or Future Readiness



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Critical asset data—whether for welds, piping systems, pressure vessels, or structural components—plays a central role in safety, reliability, and regulatory compliance. Yet the information needed to manage asset health is often buried in decades of unstructured documents—inspection reports, UT readings, MT/PT results, repair notes, spreadsheets, scanned PDFs, and vendor files.

While this article uses weld integrity as a primary example, the approach applies broadly across asset integrity programs, including piping, pressure vessels, rotating equipment, and structural systems.

With the rapid rise of AI, many organizations are asking:

“Can AI read our asset inspection data and tell us which assets need action?”

The short answer is no—not safely.

The better answer is yes, AI can transform asset integrity management if it is applied in the right part of the lifecycle. In this framework, AI structures and surfaces data. Engineers remain accountable for every integrity decision.

This article outlines a responsible, practical approach to leveraging AI that:

- Unlocks historical asset data
- Ensures future data is captured correctly
- Preserves engineering accountability: qualified engineers retain responsibility for every safety-critical decision

THE CORE PROBLEM: ASSET DATA IS TRAPPED IN UNSTRUCTURED FORMATS

With decades of inspections and thousands of assets, organizations face:

- Inconsistent document formats across years and contractors
- Data scattered across PDFs, emails, spreadsheets, and images
- Mismatched asset identifiers across systems
- Missing or ambiguous metadata
- Scanned or handwritten inspection records

This fragmentation makes it difficult to:

- Find missed action items and recommendations
- Compare inspection results over time
- Identify degradation patterns
- Build reliable predictive models

Manual review does not scale. As a result, asset owners often either over-inspect or risk missing critical locations.

This is where AI adds real value—not as a decision engine, but as a data recovery and acceleration tool.

WHY AI SHOULD NOT MAKE ASSET INTEGRITY DECISIONS

AI is powerful, but it is fundamentally unsuited for safety-critical engineering conclusions when operating alone:

- AI systems can generate incorrect or fabricated outputs (hallucinations)
- They may misinterpret technical context, units, or subtle inspection notes
- They lack deterministic traceability, which is essential for audits and regulatory reviews
- They are not engineering models and cannot replace validated formulas, rules, or physics-based analysis

As a result, AI should never be responsible for:

- Asset fitness-for-service decisions
- Repair or replacement recommendations
- Corrosion or degradation calculations
- Inspection interval planning
- Regulatory or compliance actions

However, when used correctly, AI dramatically improves everything leading up to those decisions.

THE RIGHT ROLE FOR AI: TWO PARALLEL DATA PIPELINES

The most effective AI strategy for asset integrity requires two coordinated efforts to be executed in parallel to:

1. Recover historical data using AI-assisted extraction
2. Digitally capture all new inspection data in structured form from day one

One stream resolves the legacy backlog. The other governs future data quality. Together, they form a single source of truth. While legacy data is being recovered, new inspection data continues to be generated. If that data remains unstructured, the backlog never shrinks.

STREAM 1 — HISTORICAL ASSET DATA: RECOVERING THE PAST WITH AI

AI and document intelligence technologies are ideally suited to process legacy inspection records. They can read PDFs and scanned reports to

- Extract Asset IDs
- Extract past inspection dates, locations, results, and metadata
- Parse defect descriptions
- Normalize inconsistent terminology

STREAM 2 — FUTURE ASSET DATA: CAPTURE IT CORRECTLY

At the same time legacy data is being recovered, new inspections must be digitized. New asset inspections should never re-enter the system as unstructured PDFs. Instead, future data should be collected using digital field data capture tools, standardized forms or direct integration with NDE instruments and stored in the centralized, structured asset integrity database.

FROM STRUCTURED DATA TO PREDICTIVE INSIGHT

With both historical recovery and digital-first capture feeding a common structured system, organizations can confidently apply:

- Degradation models and condition forecasting
- Anomaly detection and risk-based prioritization
- Inspection optimization

These analytics are built on validated engineering models and statistical methods—not probabilistic AI output. AI still adds value by:

- Enabling natural-language queries
- Summarizing asset histories
- Retrieving relevant records
- Explaining trends in plain language

- Clustering of anomalies across similar operating conditions
- Asset-type-specific defect recurrence

But engineering decisions remain grounded in deterministic analysis and human expertise. Machine learning does not replace engineering judgment. It augments it. Models can surface statistical signals. Engineers determine whether those signals reflect real physical mechanisms.

ENGINEERING-GOVERNED ANALYTICS: THE DOUBLE ADVANTAGE OF DATA SCIENCE + MATERIALS EXPERTISE

This is where most AI initiatives in industrial settings fail—they lack either the data foundation or the domain expertise required to interpret results correctly. There is a critical distinction between applying machine learning in isolation and applying it within an engineering-governed framework. In engineering-governed analytics, machine learning finds statistical signals. Engineers determine whether those signals reflect real physical mechanisms—and govern whether any action is warranted. The analytics serve the engineer; the engineer is never replaced by the model.

A pure data company may identify correlations but lack understanding of:

- Metallurgical degradation mechanisms
- Creep and fatigue interactions
- Inspection method limitations
- Flow-accelerated corrosion patterns

Conversely, a traditional engineering organization may possess deep materials expertise but lack the structured data foundation required to apply scalable machine learning models.

When structured asset data is combined with domain expertise in materials science and degradation mechanisms, organizations gain a dual advantage:

- Data-driven pattern recognition
- Physics-informed interpretation and validation

This combination enables:

- Higher-confidence predictions
- Reduced false positives
- Better inspection targeting
- Improved risk prioritization
- More defensible engineering decisions

Machine learning identifies where to look. Engineering expertise determines what it means.

FROM STRATEGY TO IMPLEMENTATION

Understanding the architecture is one challenge. Executing it within a safety-critical environment is another.

A parallel recovery and digital-first capture strategy requires:

- A structured asset data model aligned with asset hierarchies
- Configurable AI-assisted extraction workflows
- Embedded human validation and QA controls
- Digital inspection and field data capture capabilities
- Deterministic analytics engines
- Audit-ready traceability across the entire lifecycle

AI IN ASSET INTEGRITY	
AI CAN BE USED TO:	AI SHOULD NOT BE USED TO:
<input checked="" type="checkbox"/> Extract asset ID's	<input checked="" type="checkbox"/> Determine asset fitness-for-service
<input checked="" type="checkbox"/> Extract past inspection dates, locations, results, and metadata	<input checked="" type="checkbox"/> Recommend repairs or replacements
<input checked="" type="checkbox"/> Parse defect descriptions	<input checked="" type="checkbox"/> Calculate corrosion or degradation rates
<input checked="" type="checkbox"/> Normalize inconsistent terminology	<input checked="" type="checkbox"/> Predict asset failures
<input checked="" type="checkbox"/> Enable naturalLanguage search & Q&A	<input checked="" type="checkbox"/> Set inspection intervals
<input checked="" type="checkbox"/> Assist reviewers during data validation	<input checked="" type="checkbox"/> Generate compliance or regulatory actions
<input checked="" type="checkbox"/> Draft inspection or integrity summaries	

TABLE 1. The role of AI must be clearly defined. The above is a practical framework for where AI adds value—and where it should not be used.

At Structural Integrity Associates, this model has been implemented within our AIMS and PlantTrack platforms—integrating AI-assisted document processing, structured integrity data management, digital inspection workflows, and materials-informed analytics into a unified system.

The real differentiator is applying it within a controlled, engineering-governed framework where safety, traceability, and accountability remain paramount.

BOTTOM LINE: AI SHOULD READ ASSET INSPECTION & INTEGRITY DATA, NOT MAKE CRITICAL ASSET INTEGRITY DECISIONS

AI represents a major step forward for industrial data management—but only when applied responsibly.

The winning strategy is clear:

- Launch historical recovery and digital capture in parallel
- Use AI to unlock legacy Inspection & Asset Integrity Data
- Prevent new data from becoming unstructured debt
- Use structured databases as the single source of truth
- Apply validated engineering models and machine learning responsibly
- Keep humans accountable for safety-critical decisions

Organizations that adopt this approach gain more than efficiency. They gain a defensible, scalable, and future-ready integrity program—one that combines the speed of AI, the power of data, and the judgment of engineering expertise.

AI should read asset data. Engineers should decide asset integrity.

HUMAN-IN-THE-LOOP VALIDATION IS ESSENTIAL

For mission-critical data, human review is non-negotiable. Reviewers validate extracted data, resolve ambiguities, and ensure engineering accuracy. This hybrid approach is still an order of magnitude faster than fully manual data entry, while maintaining safety and accuracy. The validated data is stored in a centralized, structured asset integrity database, enabling the asset owner to make more informed decisions.

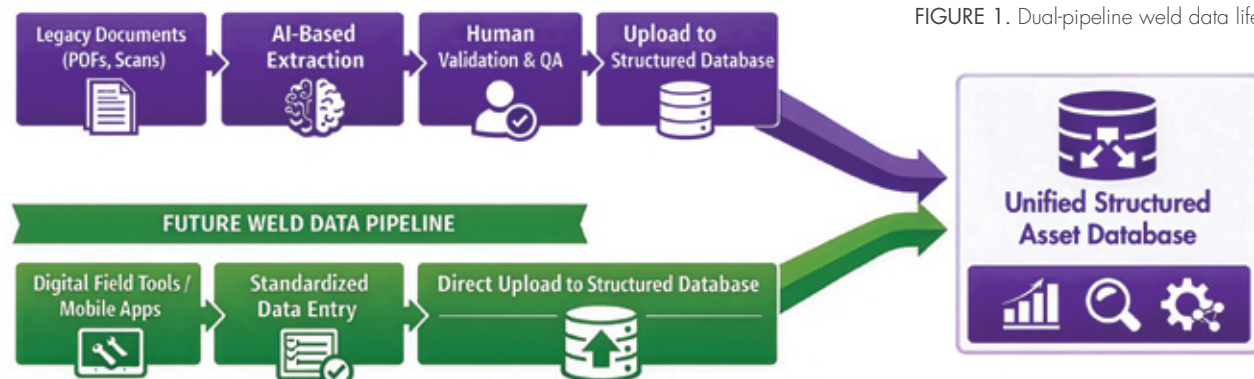


FIGURE 1. Dual-pipeline weld data lifecycle

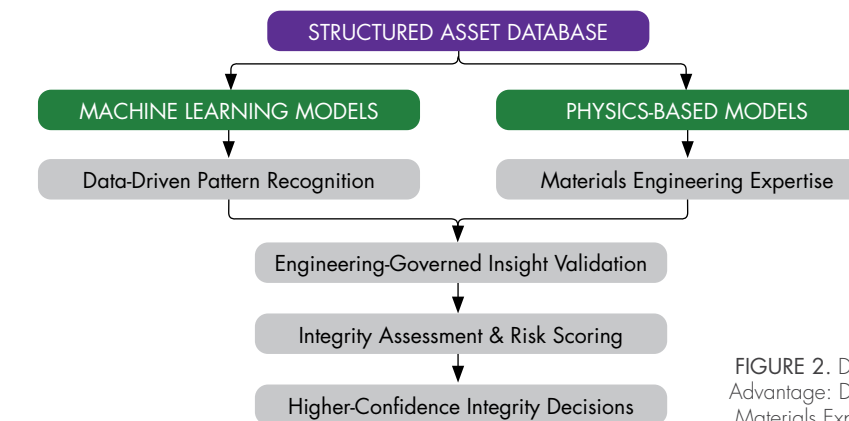


FIGURE 2. Double Advantage: Data + Materials Expertise

Rapid Recovery: Rebuilding Electrical & Instrumentation Systems After Petrochemical Refinery Fires

How post-incident response teams assess hidden infrastructure damage, restore control networks, and help process units return to service.



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INTRODUCTION

Over the past several years, C2C Technical Services, a full-service engineering contractor specializing in electrical and instrumentation construction, has developed a reputation for supporting petrochemical facilities during critical recovery periods. C2C crews frequently mobilize within hours or days of a fire or major process incident, performing damage assessments, demolition of compromised systems, and reconstruction of the electrical and instrumentation infrastructure required to restore safe operations.

The following projects, drawn from recent C2C engagements across the U.S. Gulf Coast, illustrate the range and technical complexity of post-incident



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recovery work — and the integrated engineering and field capabilities that make rapid, safe recovery possible.

Work can start as soon as the site is released. C2C’s account managers serve as dedicated points of contact — professionals who have earned the trust of plant personnel through consistent performance and a working knowledge of the facilities they support. When an incident occurs, trust allows plant management to move quickly and with confidence. C2C recruiting will begin staffing the job immediately. Our history and reputation in the industry have given us the contacts to find the right people at the right time. Our onboarding process screens applicants to ensure each team member’s qualifications fit the position.

WHEN THE TEAM IS ALREADY THERE: RAPID START AFTER AN ON-SITE INCIDENT

When C2C personnel are already on site, recovery timelines compress significantly. In March 2026, disaster struck a South Texas Chemical Plant. C2C crews were conducting a system upgrade in a neighboring unit. Our leadership was able to walk down the damaged area within days of the incident — eliminating the mobilization lag that typically delays early damage assessment. That immediate, firsthand evaluation allowed plant management to make informed decisions quickly. C2C’s ability to rapidly scale and deploy additional resources to the site meant reconstruction could begin within the same week.

Based on C2C’s performance on the ongoing project, plant management asked the team to lead the rebuild as well. Project leaders developed a recovery plan and mobilized 15 instrumentation and electrical personnel within the same week. Materials were ordered, and reconstruction work began. In less than 3 weeks, the team had grown to more than 50 on-site resources.

The ability to pivot from one scope to another — and to immediately put firsthand site knowledge to work — is what made that speed possible.

SCALE AND PRECISION: MAJOR HYDROGEN FIRE RECOVERY IN A REFINERY HYDROTREATER

Resid hydrotreaters are among the most instrumentation-dense units in a refinery — fire damage in one doesn’t just destroy equipment, it severs the control infrastructure that keeps the entire process safe. When a major hydrogen fire struck one such unit, the extent of damage to wiring systems, junction boxes, and instrumentation

throughout the unit quickly made clear that extensive reconstruction of its electrical and instrumentation systems was required before restart could be considered. C2C mobilized within 12 hours and spent the next four months systematically working through demolition, reconstruction, and verification across the unit.

HYDROTREATER FIRE RECOVERY BY THE NUMBERS

- 75 personnel at peak workforce
- 200,000 ft of compromised instrument cable removed
- 174,000 ft of new instrument cable installed
- 20,000 terminations completed
- 1,300 instrument loops verified
- 58,000 work hours
- Zero safety incidents

Scaling to a peak workforce of 75 required more than a willingness to mobilize — it required the ability to rapidly source, vet, and deploy qualified electricians and instrument technicians on short notice. C2C’s recruiting team was a decisive factor in meeting that demand. Working in close coordination with operations, they sourced and onboarded a preliminary workforce within days of the site being cleared, without relaxing the qualification standards that work in a safety-critical refinery environment demands. In the weeks that followed, the team continued to scale the workforce, adding personnel in step with evolving field conditions and emerging scope as it was identified in real time.

Crews demolished and rebuilt power and control circuits serving multiple 480-volt motor systems, repulled 12,000 feet of cable, installed new cable tray, and constructed splice boxes to restore both power and control wiring.

CONTINUED...



What set this project apart was the depth of engineering integration running parallel to field work. Because the reconstruction required significant changes to the infrastructure, C2C engineers redesigned portions of the control infrastructure — relocating splice boxes and rerouting cable tray systems to match the rebuilt unit. They developed or revised approximately 800 instrument loop drawings in real time. When original instruments were unavailable, engineers specified replacements.

That integration of engineering and field work — operating simultaneously rather than sequentially — was central to returning the unit to safe operation quickly and without a single safety incident across 58,000 work hours.

ENGINEERING UNDER PRESSURE: REFINERY ALKYLATION UNIT RECOVERY

Alkylation units are critical to refinery gasoline blending operations — extended downtime disrupts production planning and fuel supply commitments. When a hydrocarbon release caused a fire in one refinery’s alkylation unit, returning the unit to service quickly became a top operational priority.

The fire was brief, but heat and flame exposure compromised wiring, junction boxes, and field instrumentation across the process area. C2C mobilized construction crews within a day of the incident. Over the next two months, a peak workforce of 25 technicians and supervisors removed damaged infrastructure, reinstalled cable, rebuilt terminations, and restored connections throughout the unit.

The compressed restart timeline made coordination especially critical — and created a challenge that only integrated operational support could solve. Original instrumentation could not be sourced quickly enough to meet the startup schedule, and some existing designs

required modification to accommodate operational constraints. C2C technical leaders worked directly alongside client representatives to evaluate each application, identify alternate instrumentation technologies that met both process requirements and the accelerated schedule, and provide updated reference drawings that bridged gaps between existing design documentation and actual field conditions.

When reconstruction was complete, technicians performed loop checks and functional testing to confirm that signals from field instruments were correctly transmitted to control systems before the unit was brought back online.

Technical support on the front line was critical to maintaining the restart schedule. The unit returned to service without a safety incident.

DUAL-SCOPE EXECUTION: CHEMICAL PLANT PROCESSING UNIT REBUILD

Processing units rely on tightly integrated electrical and instrumentation systems, which means post-incident reconstruction often expands in scope as demolition reveals damage that wasn’t visible from the outside — a challenge compounded when recovery must proceed alongside other plant work.

When a fire damaged a chemical plant unit in East Houston, the C2C account manager’s strong relationship with the maintenance team made C2C the first call—enabling a rapid damage assessment and coordinated recovery within two days of the incident. Over the next two months, the workforce expanded to a peak of 28 electrical and instrumentation technicians and supervisors. Crews demolished damaged wiring systems, junction boxes, and field instrumentation compromised by heat and smoke, then rebuilt — installing new wiring, restoring control connections, and preparing systems for functional checkout.

What distinguished this project was its dual scope: capital improvement work was performed in parallel with the fire recovery effort, requiring close coordination between C2C construction crews and plant engineering personnel. Managing both scopes simultaneously — without compromising the safety or the schedule of the recovery — demanded flexible, experienced field execution and tight engineering integration throughout.

Despite conditions typical of post-incident work, where crews routinely encounter previously hidden damage as demolition progresses, the unit was rebuilt and prepared for startup without a safety incident.

WHAT PLANT OPERATORS FACE AFTER A PROCESS FIRE

- Hidden wiring damage often extends far beyond visible fire exposure
- Documentation may require significant reconstruction
- Alternate instrumentation may be needed when original devices are unavailable
- Rapid coordination between engineering and field technicians accelerates recovery
- Early damage assessment can shorten unit restart timelines
- Existing contractor relationships on site can compress initial mobilization by days

FROM UNCERTAINTY TO RESTART

Across all of these projects, a consistent pattern emerges. Fires damage more than what’s visible — wiring hidden inside cable trays, conduits, and junction boxes; documentation that no longer reflects field conditions; control systems that cannot be restarted until every loop is verified. The full extent



of the work rarely becomes clear until demolition is already underway.

Successful recovery at scale is an organizational effort that extends beyond engineering and field execution. Sales and business development teams define scope and align expectations with the client from the first call. Construction and Engineering drive real-time coordination across a workforce that may grow from a handful of people to dozens within days. And recruiting is often the decisive factor — sourcing, vetting, and onboarding qualified electricians and instrument technicians quickly enough to meet a timeline that can't wait. When those functions operate in alignment, the pace of recovery reflects it.

This coordination compresses timelines, prevents rework, and keeps recovery on track even when the scope keeps changing.

For petrochemical operators, the speed and accuracy of that work matter. Process units offline for extended periods represent significant operational and economic losses. The goal is always the same: restore damaged electrical and instrumentation infrastructure safely and efficiently so that critical units can return to service.

Rapid Recovery Requires:

- Excellent pre-mobilization communication between the site and C2C leadership
- Accurate instrumentation documentation
- Cross-disciplinary recovery teams — engineering, operations, HR, and sales
- Experienced electricians and instrument technicians
- Real-time engineering support
- Expedited recruiting and workforce deployment
- Rapid material sourcing

- Detailed equipment sell-off procedures
- Continuous coordination with operations teams

C2C Technical Services combines rapid mobilization with integrated engineering and field execution to help petrochemical facilities move from uncertainty to restart. When our clients face their most critical moments, C2C rises to its highest level of performance. That confidence is earned—and it’s why our clients turn to us first, for both planned initiatives and unforeseen events.



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