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Structural Integrity Associates, Inc.®

NEWS & VIEWS

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Forecasting the Life of a Mass Concrete Structure pg.15

A CASE STUDY FROM THE FERMILAB LONG BASELINE NEUTRINO FACILITY

CEO Message

MARK W. MARANO
President and CEO
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We live in tumultuous times. I can't be more thankful for our staff of world class employees and their resilience to continue to deliver for our clients through the pandemic. Now that we see the backside of Covid restrictions you can feel the energy, the excitement of working more directly with clients and each other in our company. In February, I was pleased to be able to bring the SI Leadership team together to collaborate and discuss how we grow as a team, as a company, and as a technology provider. Seeing the creativity and energy of the SI Leadership in person was invigorating. The outcome of coming together was a renewed focus on clients, markets, and innovation.

We are off to a good start for the year and have been fortunate to add signifcant engineer talent to our staff. SI's ability to continue to deliver expert solutions has never been better. And, this issue of News and Views highlights where we've been making advances in new asset management techniques like acoustic emissions testing and how SI's structural expertise is helping to make America's particle physics and accelerator laboratory a reality.

On the strategic front, one of our new hires was the addition of Ken Canavan to the SI Leadership. Ken supported me previously as the Chief Technology Officer for the nuclear OEM Westinghouse and is a welcomed addition to the team. In Ken's role as Chief Revenue Officer, we will lean into Ken's broad technical expertise and leadership to grow SI. Please join me in welcoming Ken and all our new staff.

We look forward to serving you.

KEN CANAVAN JOINS SI AS VICE PRESIDENT, GROWTH / CHIEF REVENUE OFFICER

Ken comes to SI as the former Chief Technology Officer (CTO) of the Westinghouse Corporation and, prior to that, EPRI as the Director, Engineering. Ken's expertise includes leading small and large teams of engineers and scientists to develop impactful global research and development portfolios. These portfolios are aligned with the business and growth strategies and are used to drive innovative solutions to create customer value. Ken also has hands-on experience in the areas of nuclear plant equipment reliability, plant engineering, instrumentation and control, maintenance, and risk and safety.

KEN CANAVAN
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KEN'S KORNER

I am extremely excited to be here at SI. I have been in the industry a long time, worked in many companies large and small, and seen many things but did not know the talent and innovation that is here at SI. At SI we live up to our motto "Powered by Talent and Technology". I also see the many changes that have taken place over the last few years - and that more changes are coming - but they all lead to a brighter future which I am proud to be part of. For my part, I plan to lean in and get my hands dirty (being a techy at heart) all with an action-oriented approach to growth through service to the energy industry and, most importantly, our customers.

The Paul Zayicek Memorial Scholarship

Remembering a Friend

(LEFT TO RIGHT) SI employees Randy McDonald, Jarrod Bradley, Jeff Cavanagh, Jeff Milligan and Rodney Stephens, Charlotte's ASNT Charmain & CPCC NDE Instructor.

CENTRAL PIEDMONT COMMUNITY COLLEGE FOUNDATION

THE AMERICAN SOCIETY FOR NONDESTRUCTIVE TESTING®

The Charlotte section of the American Society of Nondestructive Testing (ASNT) supports a deserving student of the Nondestructive Examination Technology program at Central Piedmont Community College (CPCC) through an annual scholarship. In 2019, the scholarship was renamed in memory of long time ASNT fellow and former Structural Integrity employee, Paul Zayicek.

The Paul Zayicek Memorial Scholarship supports students in the CPCC NDE program, of which a handful of SI NDE professionals are graduates. Structural Integrity is extremely proud to support this foundation in Paul's memory and to help sustain the future of the program. Along with this scholarship, SI is excited to announce its first NDE Co-op program with CPCC in our Energy Services Group. This co-op position will provide an opportunity for students to be exposed to NDE through assessing the condition of critical industrial components and offering both hands-on and in-field experience.

For more information about CPCC's scholarship program, please visit https://www.cpccfoundation.org/about/.

In this Issue

PEGASUS

A Versatile Tool for Used Fuel Modeling

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INTRODUCTION

PEGASUS, a finite element fuel code developed at SIA, represents a new modeling paradigm. This new paradigm treats all fuel behavior regimes in one continuous analysis. This approach differs significantly from the current conservative practice of bounding analysis to ensure uncertainties are accounted for which results in sub-optimal used fuel management strategies. Using PEGASUS in used fuel evaluation results in significant savings in engineering cost and work force utilization, reduces conservatism, and provides flexibility in the management of used fuel.

PEGASUS, a finite element fuel code developed at SIA, represents a new modeling paradigm. This new paradigm treats all fuel behavior regimes in one continuous analysis.

The PEGASUS code was developed for modeling LWR fuels and has been validated against measurement data on test reactor and commercial fuel rods. An overview of the code

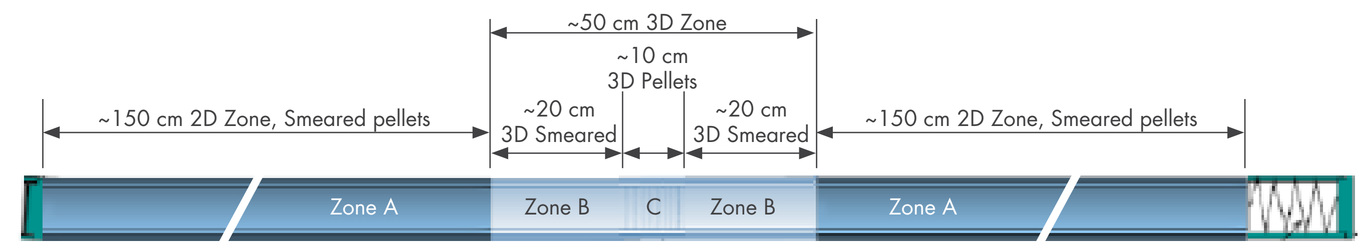


FIGURE 1. Schematic of Fuel Rod Model for Fuel Cycle Analysis

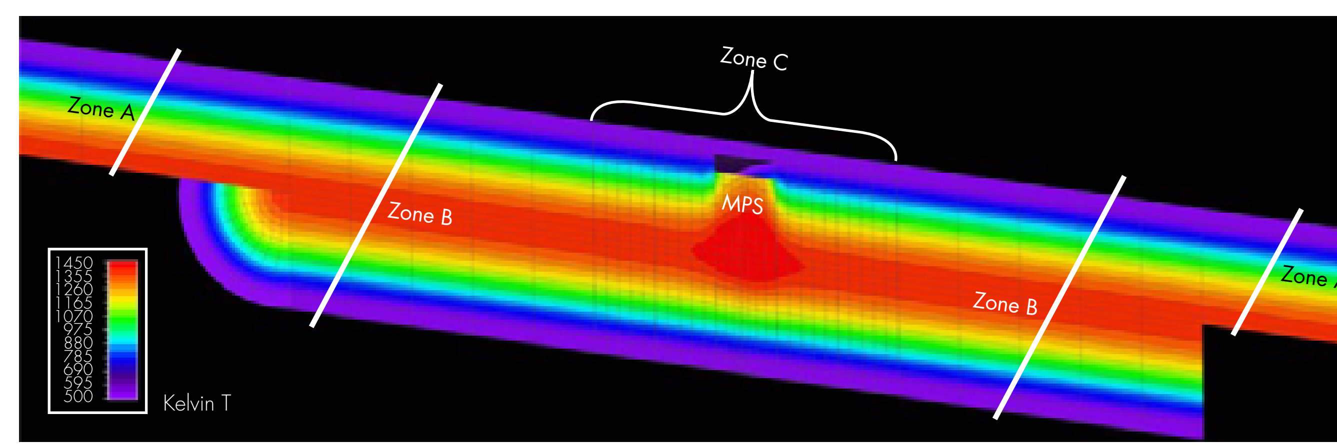
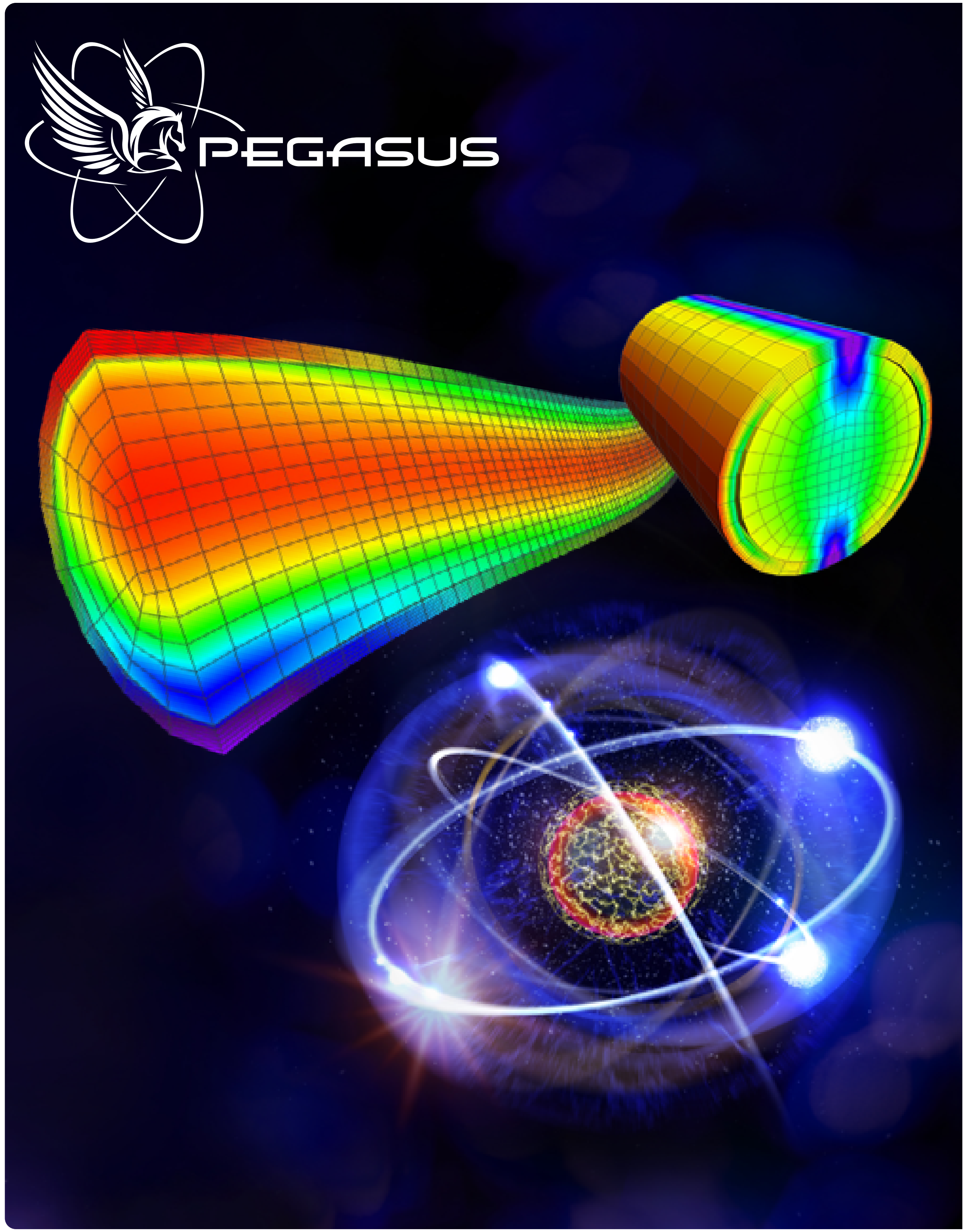


FIGURE 2. Temperature Contour of 2D/3D Hybrid Modeling



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features and the status of code validation was reported in Ref. [1].

ONGOING DEVELOPMENT

The ongoing development further improves the integral analysis to adopt a hybrid 2D / 3D modeling capability: a full-length fuel rod is modeled as a composition of several finite element mesh zones (shown in Figure 1), each of which is suited for simulating a behavior regime in the fuel cycle.

Figure 2 shows the schematic of temperature distribution for all fuel rod zones. This hybrid modeling would augment the implementation of used fuel modeling methodology by combining the global 2-D fuel performance modeling and 3-D structural analysis in one platform.

EXAMPLE

Consider the case of an in-reactor irradiation of a commercial PWR fuel rod which is subject to a constant power in a two-year irradiation followed by a hypothetical 9-m drop of a spent fuel cask. In addition to the conventional 2-D fuel modeling, a 3-D model is created at the mid-section of the fuel rod, and the fuel response under combined bending and pinch loading is modeled. Figure 3 shows the stress of the 3-D fuel segment at its peak load condition, an indicator to the fuel failure potential. This case illustrates that the PEGAUS modeling method preserves the material property changes in the in-reactor operation fuel behavior modeling regime, and can generate the used fuel responses with high fidelity in its 3-D model.

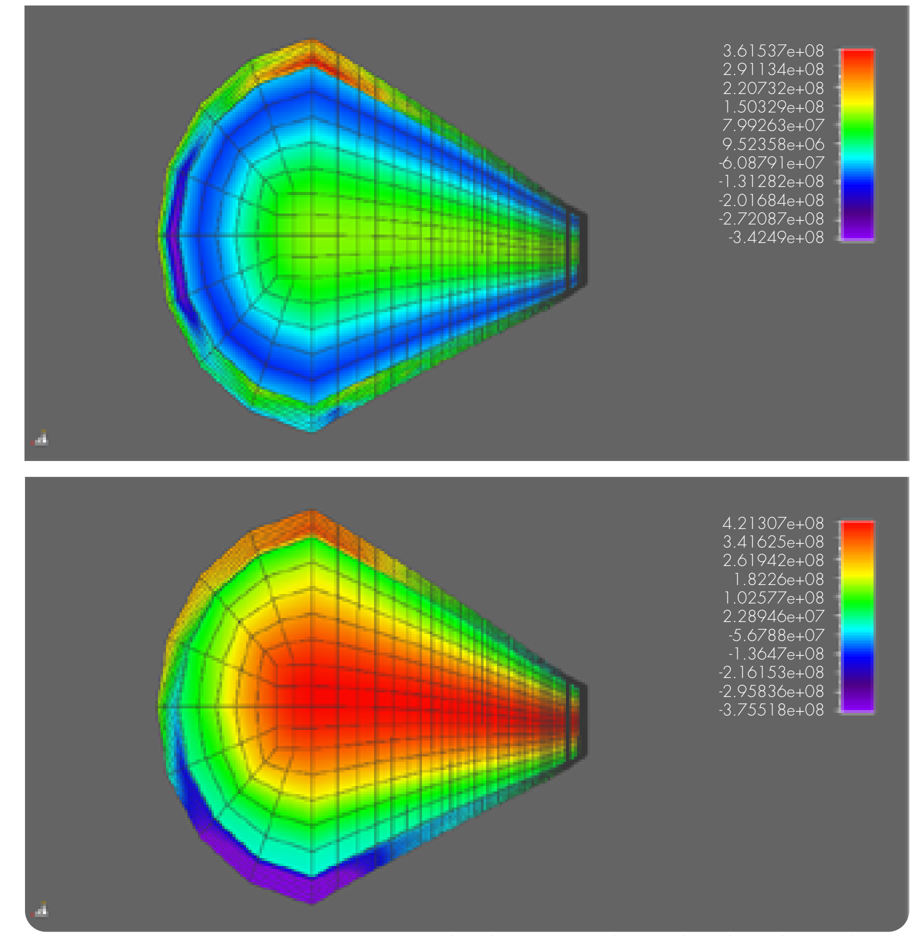

FIGURE 3. Spent Fuel Rod Segment under Combined Bending and Pinch-Loading in 9-m Drop Accident

CONCLUSION

PEGASUS, as a total-fuel-cycle-simulator, treats, with equal high fidelity, the modeling of fuel behavior in a seamless transition from the active fuel cycle to back-end cycle using a single, multi-dimensional finite element model. This integral approach makes it possible to perform high-fidelity assessments of used fuel failure resistance in regulatory hypothetical accident conditions. We expect that this first-of-a-kind high-fidelity approach can result in enormous savings in engineering cost and work force utilization and offer significant benefits to clients.

Reference

[1] W. Liu, J. Rashid, B. Lyon, M. Kennard, and A. Mai, "PEGASUS: A Generalized Fuel Cycle Performance Code," TOPFUEL 2021 (2021).

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Managing Piping Assets

Software Automation

Driving Forces for Digital Transformations:
Paper Reduction (68%)
Online Training (54%)
Risk Management/Prediction (39%)
Social Media Integration (63%)
IT Automation (50%)

From Tech Pro Research, %'s reflect rate of respondents who believe digital transformation will significantly impact indicated categories.

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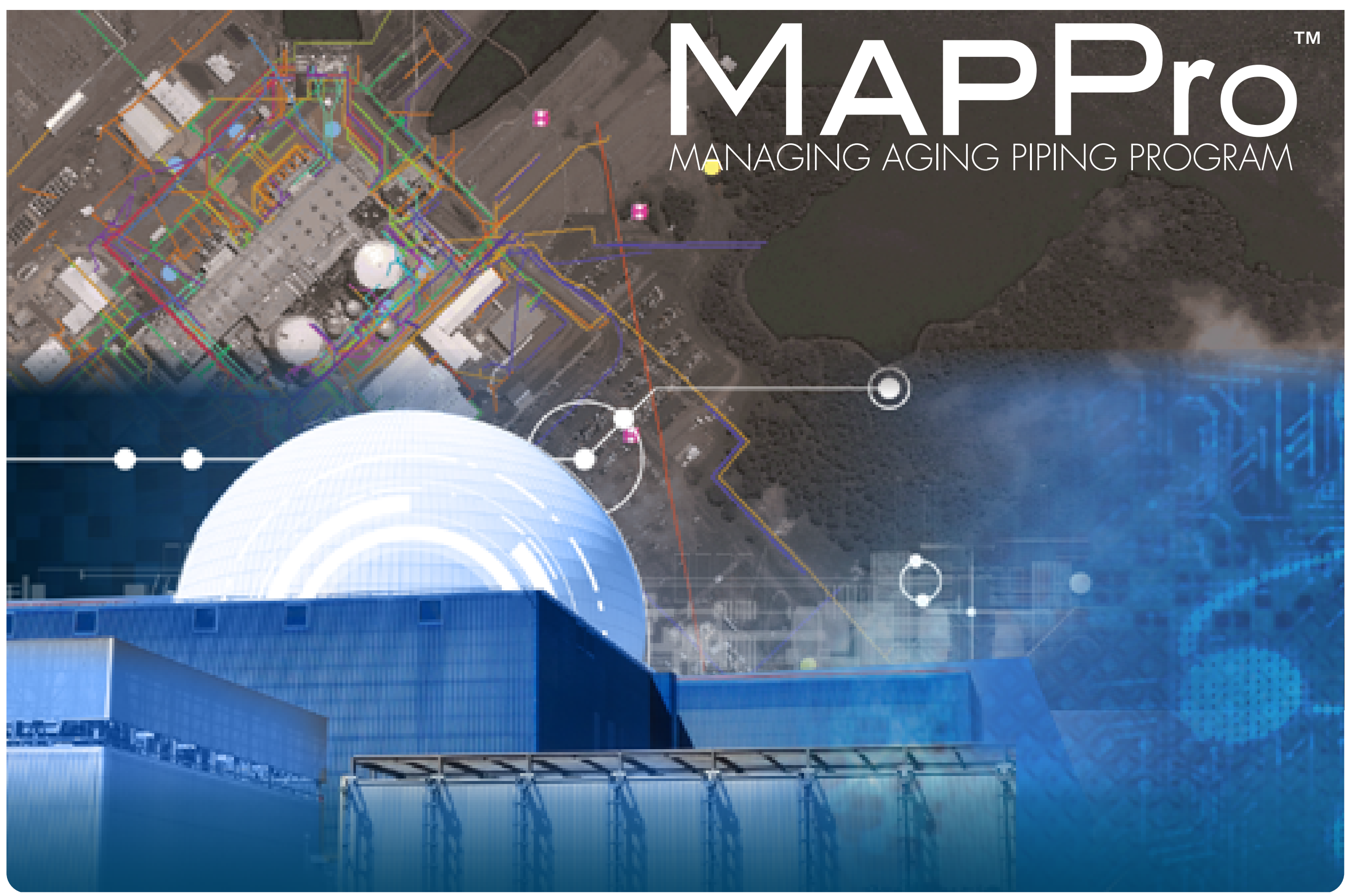

A fundamental tenant of engineering is that where inefficiencies exist, innovation is next. This is especially true in the ongoing era of digital transformation, as software-based automation eliminates mundane, trivial tasks and enables increased focus on value-add activities. A recent poll of workers in the tech industry found that 70% of their respective companies have either committed to or are developing a transformation strategy, with varying emphases (see sidebar). The energy sector is no stranger to these innovations, and while the pace and scope of digital transformation may not appear to match that of driverless cars or moon rockets, its societal impacts are comparably widespread.

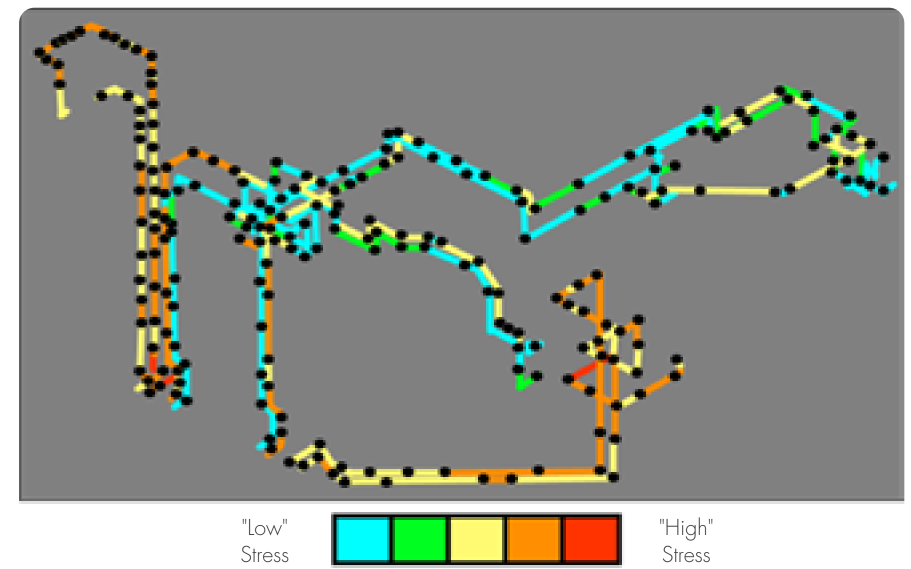

FIGURE 1. Risk and Stress Value Layers

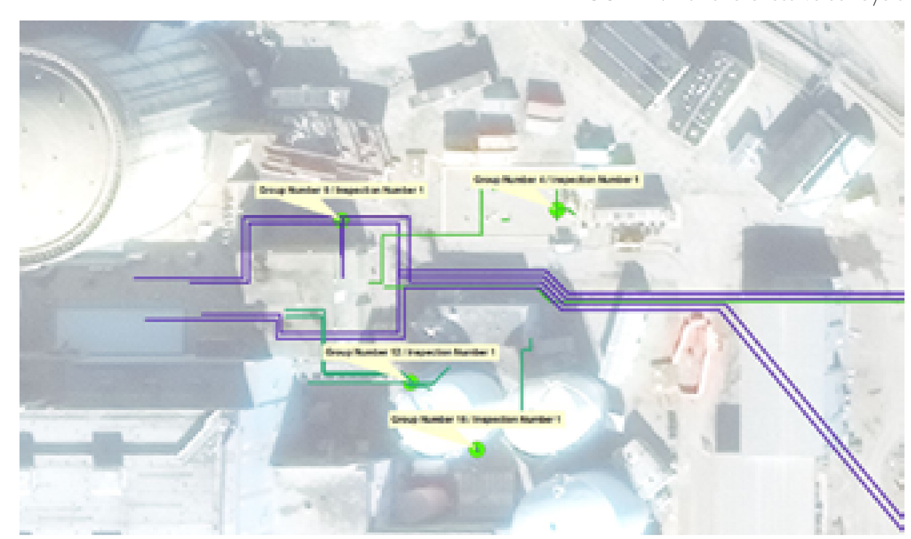

FIGURE 2. Inspection Grouping in Action

Historically, SI has been recognized as a leader in highly technical subject matter areas such as fracture mechanics, material degradation, and nondestructive examination. In many cases, this expertise is aided by digital or software innovations that enable efficient data handling, novel computer aided visualizations, and dynamic performance of complex calculations. In this vein, our MAPPro software is designed to aid in management of aging piping assets and has been an integral resource to the nuclear industry since its inception in 2009. In the period since, the software has supported asset owners in performing sophisticated risk analyses, managing and planning inspections, and prioritizing actions to maximize value and minimize cost. Select examples include an innovative compilation of data layers that helps plan inspections by identifying areas of concern based on a multitude of variables (Figure 1). Inspection planning is further aided by using GIS to effectively stack said layers to view planned inspection locations and eliminate redundancies (Figure 2).

Recognizing the industry trend toward broad digitization, SI recently made significant investments in the MAPPro platform, transitioning it from a desktop application with a fixed toolset to a web-based platform with a significantly upgraded toolset and extensive customizability. The new user interface is simple and intuitive while maintaining all existing functionality. A growing number of tools and features are being added to simplify recurring tasks and encourage use beyond the traditional buried piping engineers.

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Examples of these new / upgraded features in MAPPro Version 4.0 are as follows:

- Widespread access to MAPPro's data management and visualization features (read-only access can be granted to virtually anyone within a given domain).
- Easy import and population of tabular data for multiple locations / segments via new Microsoft Excel integration.
- Calculate piping fitness for service per applicable guidelines (e.g., NEI-09-14 Appendix-C), incorporating inspection results and corrosion projections.
- Efficiently store and retrieve inspection reports and results (including grid based NDE data).
- Automatic software updates occur in the background (nothing to install, ever!)

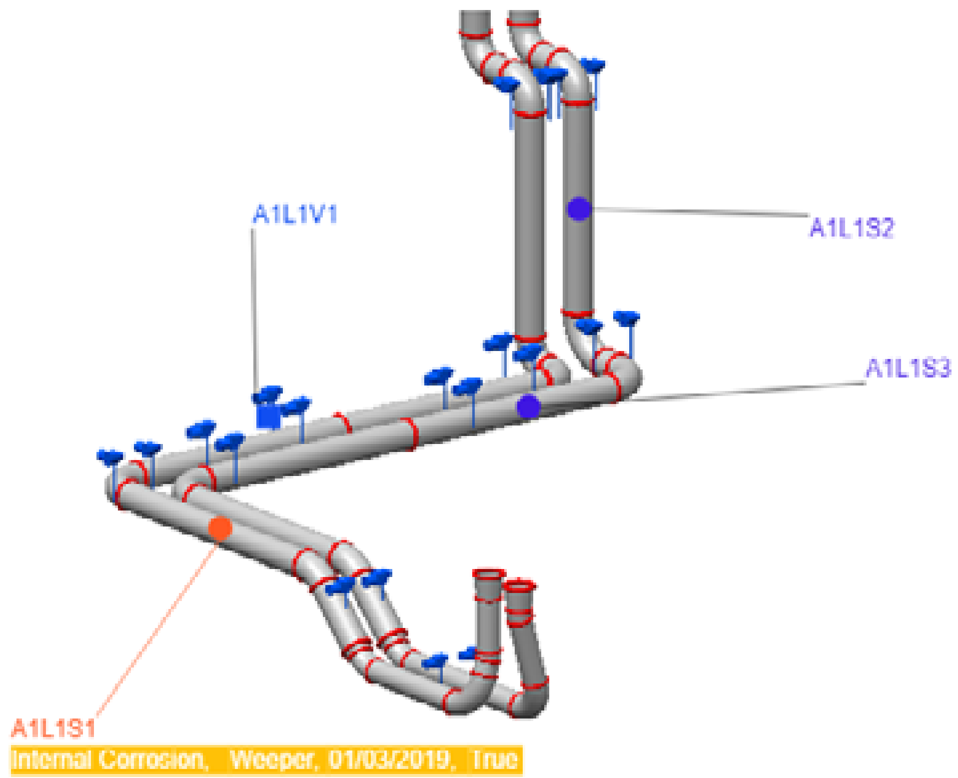

FIGURE 3. Forthcoming MAPPro Pipe Builder Tool

We're proud of the enhancements made thus far and we have big plans for additional tools and features to make MAPPro the ultimate platform for management of piping systems. Most of our development plans are directly in response to feedback or suggestions from our user community.

One upcoming feature that we're so excited about we can't keep it a secret is our new Pipe Builder tool, which enables users to graphically add components to the MAPPro database piece-by-piece. This is a significant departure from the historical approach, which required SI to "digitize" information from existing drawings or stress models and provided an updated database image.

Now, individual pipe segments can be defined and graphically selected, then associated with various inspections or findings (see Figure 3). This approach streamlines communication by allowing anyone (i.e., engineers, technicians, managers) to reference the "location" of leak in an intuitive, repeatable fashion. The tool flexibly supports import of individual pipes / lines or more complex assemblies, and seamlessly handles back-end associations of inspection records, a process that was significantly more-involved under the historical approach which led to Figure-2. The resulting data can then be queried by various analytics libraries to make informed predictions about component / system life and future inspection needs.

SI's goal for MAPPro development is simply to equip piping asset integrity management engineers with a robust platform to simplify common tasks and empower advanced decisions. We are actively engaged with numerous clients to support the upgraded platform and implement some of the new features, and we welcome all MAPPro users to engage with SI for that continued support. If you have any questions on these efforts or would like a demonstration of how MAPPro can help you accomplish your program objectives, please contact Adam Roukema (aroukema@structint.com or 303-542-1434).

Acoustic Emission Testing

Streamlining Requalification of Heavy Lift Equipment

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BACKGROUND

Proper control of heavy loads is critical in any industrial application as faulty equipment or practices can have severe consequences. The lifting technique, equipment, and operator qualifications must all meet or exceed applicable standards to ensure industrial safety. The significance of heavy lifts at commercial nuclear facilities is, perhaps, even greater. In addition to the consequences of an adverse event that are common to any industry (bodily injury or human fatality, equipment damage, etc.), the nuclear industry adds additional challenges. Such an adverse event in the nuclear industry can also affect (depending on the specific lift) fuel geometry / criticality, system shutdown capability, damage to safety systems, etc. One example of a critical lift in nuclear power facilities is the reactor vessel head / reactor internals lift.

The requirement to inspect the heavy lifting equipment for structural integrity is prescribed in NUREG-0612, Control of Heavy Loads At Nuclear Power Plants, as enforced by NRC Generic Letter 81-07. The aforementioned NUREG document describes specific requirements for special lifting devices. The requirements prescribed include:

- Special lifting devices are subject to 1.5X rates load followed by visual inspection, or
- Dimensional testing and non-destructive examination (NDE) of the load bearing welds

In the case of the former requirement, it can be difficult or even dangerous to test these lift rigs, which are designed to carry over 150 tons, at a factor of 1.5x. In the case of the latter requirement, employing the more traditional NDE techniques of MT, PT, and UT to inspect the lift rigs can be costly (both in terms of labor and radiological dose) and time consuming, in terms of impact to outage critical path, depending on when the inspection is performed. In PWRs or BWRs, inspections are performed in the reactor containment, or radiation-controlled area, and are typically only performed during the outage.

Ultimately, the NRC requires licensees to determine how they will comply with the NUREG requirements.

One method that has been adopted (primarily by PWR plants) is Acoustic Emission (AE) testing. AE testing is a non-destructive testing process that uses high-frequency sensors to detect structure-borne sound emissions from the material or structure when under load. The process detects these acoustic emission events and, based on sensor locations and the known sound velocity and attenuation, can identify the approximate location of the sources or areas of concern. If such areas are identified, based on analysis of the data captured under load, those areas must be further investigated to characterize the indication. Such additional techniques may include surface examination (MT or PT), or volumetric UT to precisely locate, characterize, and size any indications.

> Employing an advanced technique such as AE can significantly reduce the time required to perform this evolution, also reducing both the cost and dose associated with meeting the NUREG requirements.

The original deployment of this method was championed by a utility in the mid-1980's and has since been adopted by many of PWR plants as the preferred inspection method.

APPLICATION OF AE TESTING

In 2021, SI began offering AE testing services for reactor head lift rigs, including the qualified personnel, equipment, and tooling necessary

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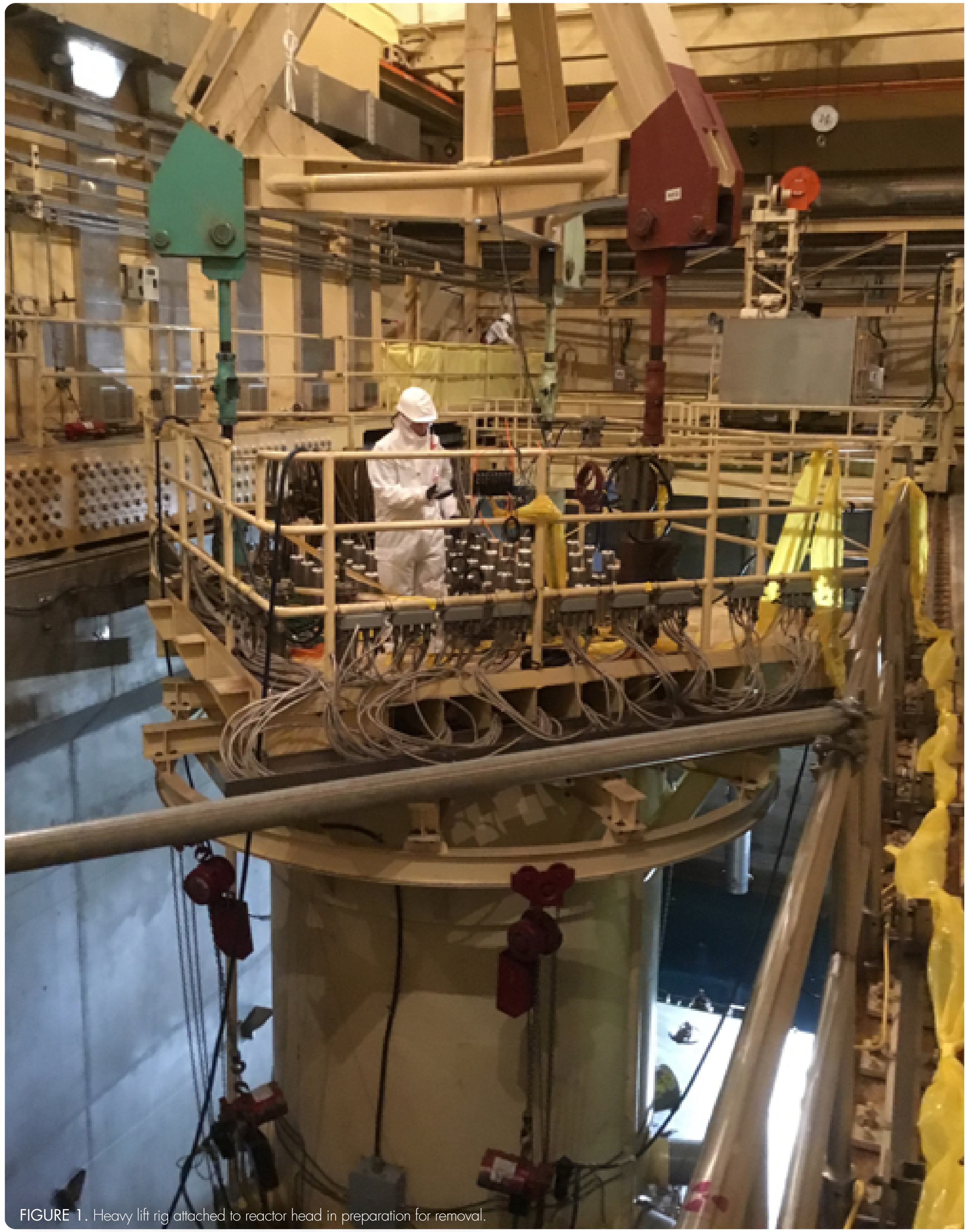

FIGURE 1. Heavy lift rig attached to reactor head in preparation for removal.

to perform this work. Our first implementation was at a nuclear plant in the Southeast US in the fall of 2021, and additional implementations are contracted in the spring and fall of 2022, and beyond. There are several advantages to AE testing that make it uniquely suited for the vessel head (or internals) lift application. First, AE is a very sensitive technique, capable of picking up emissions from anomalies that cannot be detected by traditional techniques. This allows for identifying areas of potential / future concern before they are an imminent safety danger. Second, AE sensors are capable of sensing relevant emissions from a reasonable distance (up to 10 ft or more) between source emission and sensor placement. As such, AE testing can monitor the entire lifting structure with a reasonable number of sensors (typically less than 20) placed on the structure. Thus, sensors are strategically placed on the structure where failure is most likely – i.e., the mechanical or welded connections (joints) between structural members.

This strategic sensor placement has another inherent advantage unique to the AE process. If an indication is noted, the system has the capability to isolate the approximate source location (generally within a few inches) of the emission. This is accomplished using a calculation that considers the arrival time and intensity of the acoustic emission at multiple sensor locations. This is very beneficial when an indication requiring subsequent traditional NDE is noted as specific areas can be targeted, minimizing the scope of subsequent examinations.

> The ability of AE testing to rapidly screen the entire lift structure for active damage growth saves time and money over the traditional load testing and comprehensive NDE approaches.

Finally, and perhaps most importantly, the test duration is minimal and is, effectively, part of the standard process for reactor vessel head removal. Sensor placement is performed during the normal window of plant cooldown and vessel head de-tensioning, so outage critical path is not compromised. The actual test itself is performed as part of the head (or internals) lift; that is, when the head breaks from the vessel flange (and maximum load is achieved), the load is held in place for 10 minutes while monitoring for and recording acoustic emission activity. Each sensor (channel) is analyzed during the hold period and a determination is immediately made at the end of the 10-minute period as to whether the lifting rig structure is suitable for use. Unless evidence of an imminent failure is observed, the lift immediately proceeds to the head (or internals) stand. The gathered data are also analyzed on a graded basis. Depending on the energy intensity of the events detected at each sensor, subsequent recommendations may range from: 'Good-as-is', to 'recommend follow-up NDE post-outage'.

FIGURE 2. Lift rig turnbuckle outfitted with AE sensor.

The basic process of implementation is:

- Calibrate and test equipment offsite (factory acceptance testing)
- Mount sensors and parametric instrumentation (strain gauges, impactors) during plant cooldown and de-tensioning
- System check (Pencil Lead Breaks (PLBs), and impactor test)
- Lift head to the point of maximum load
- Hold for 10 minutes
- Continue lift to stand (unless evidence of imminent failure is observed)
- Final analysis / recommendations (off line, for post-outage consideration)

SI VALUE ADD

During our fall 2021 implementation, SI introduced several specific process improvements over what has been historically performed. These advances have enhanced the process from both a quality and schedule perspective. A few of these enhancements are:

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COMMERCIAL GRADE DEDICATION OF THE SYSTEM

SI developed and deployed a commercial grade dedication process for the system and sensors. Often, licensees procure this work as safety-related, meaning the requirements of 10CFR50 Appendix B apply. The sensors and processing unit are commercially manufactured by a select few manufacturers that typically do not have QA programs that satisfy the requirements of 10CFR50, Appendix B. For this reason, SI developed a set of critical characteristics (sensor response, channel response to a simulated transient, etc.) and corresponding tests to validate that the system components

FIGURE 3. Close-up of AE sensor.

are responding as-expected and can be adequately deployed in a safety-related application.

EMPLOYING STRAIN GAUGES FOR MAXIMUM LOAD

The arrival time of an acoustic emission at one of the installed sensors is measured in milliseconds. For this reason, it is critical to initiate the 10-minute hold period precisely when

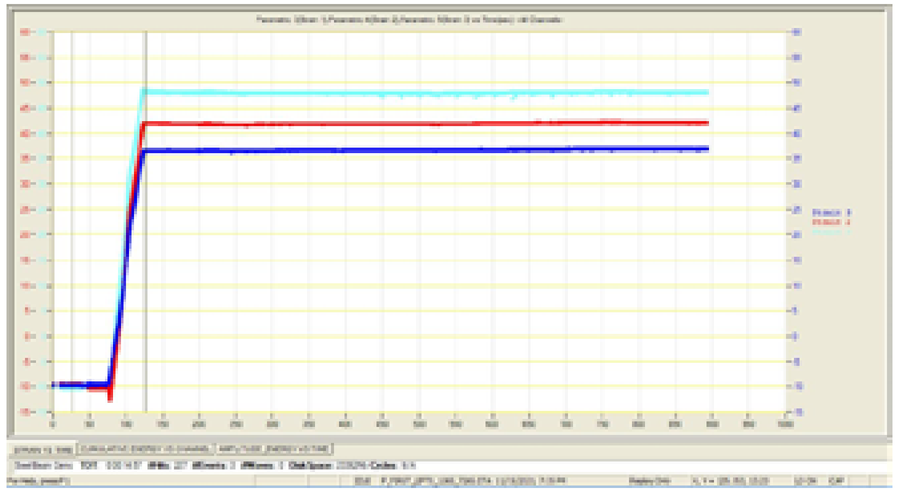

FIGURE 3. Strain gauge output showing precise timing of peak load on lift rig.

peak load is reached. The historical method for synchronizing peak-load with the start of the hold period relied on the use of a stop-watch and video feed of the readout from the containment polar crane load cell. When the load cell appears to max out, the time is noted and marked as the commencement of the test. This approach can be non-conservative from a post-test analysis perspective as the data before the noted start time is typically not considered in the analysis. As the strain gauge correlation provides a much more precise point of maximum load that is directly synchronized with the data acquisition instrument, it is more likely that early acoustic emissions, which are often the most intense and most relevant, are correctly considered in the analysis.

REMOTELY ACTUATED IMPACTORS

One of the methods used in AE testing to ensure that the sensors are properly coupled and connected is a spring-loaded center punch test. This test employs a center punch to strike the component surface, resulting in an intense sound wave that is picked up by all the sensors. However, this test has historically been performed manually and required someone to physically approach and touch the lifting equipment. In certain applications, this can be a safety or radiological dose issue and, additionally, can add time to an already time-critical plant operation. For this reason, SI has introduced the use of remotely actuated impactors to perform this function. The result is equivalent but entirely eliminates the need to have personnel on the lift equipment for the test as this task is performed remotely and safely from a parametric control center.

CONCLUSION

Employing cutting-edge AE testing for your vessel head / internals heavy lift can save outage critical path time, reduce radiological dose, and identify structural concerns early in the process. All of this leads to inherently safer, more efficient verification of heavy lift equipment.

SI has the tools, expertise, and technology to apply cutting-edge AE testing to your heavy lifts. SI is committed to continually improving the process at every implementation. Improvements in software processing time, and setup / preparation time are currently in-process. Finally, other potential applications for the method are also possible, and we stand ready to apply to the benefit of our clients.

Forecasting the Life of a Mass Concrete Structure, Part One

A Case Study from the Fermilab Long Baseline Neutrino Facility

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All around us is aging concrete infrastructure. From the dams holding back water, to the nuclear power plants creating carbon free electricity, to the foundations of our homes and offices. Though many advances have been made in the design of concrete structures, how do we know these structures will stand the test of time. Can we see the future of a concrete structure? Can we know the damage built into a structure during construction, normal life, and extreme events?

Answer: Yes we can.

BACKGROUND

In Batavia, Illinois a facility being built that is the first of its kind in the world. Fermilab's Long Baseline Neutrino Facility will accelerate protons using electromagnets up to incredible speeds in a particle accelerator. After traveling through the campus, the particles are redirected to a graphite target where the collision breaks them into their component particles: pions and muons. These components decay and are segregated off. What is left is believed to be the building blocks of the universe: neutrinos, which can pass undisturbed through matter. A beam of neutrinos passes through near detectors and travels over 800 miles underground

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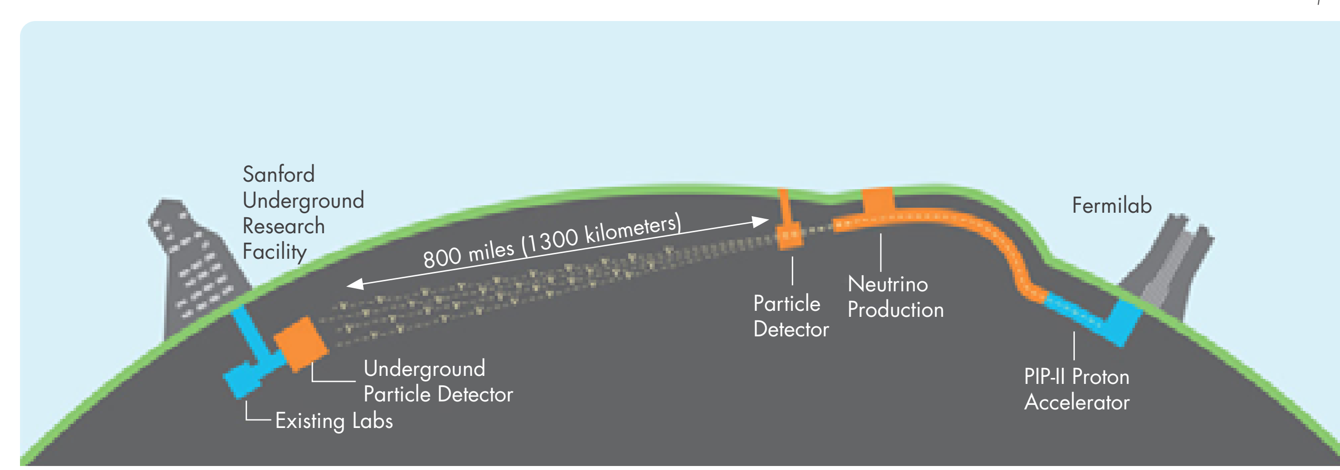

FIGURE 1. Fermilab Long Baseline Neutrino Facility (source https://mod.fnal.gov/mod/stillphotos/2019/0000/19-0078-02.jpg)

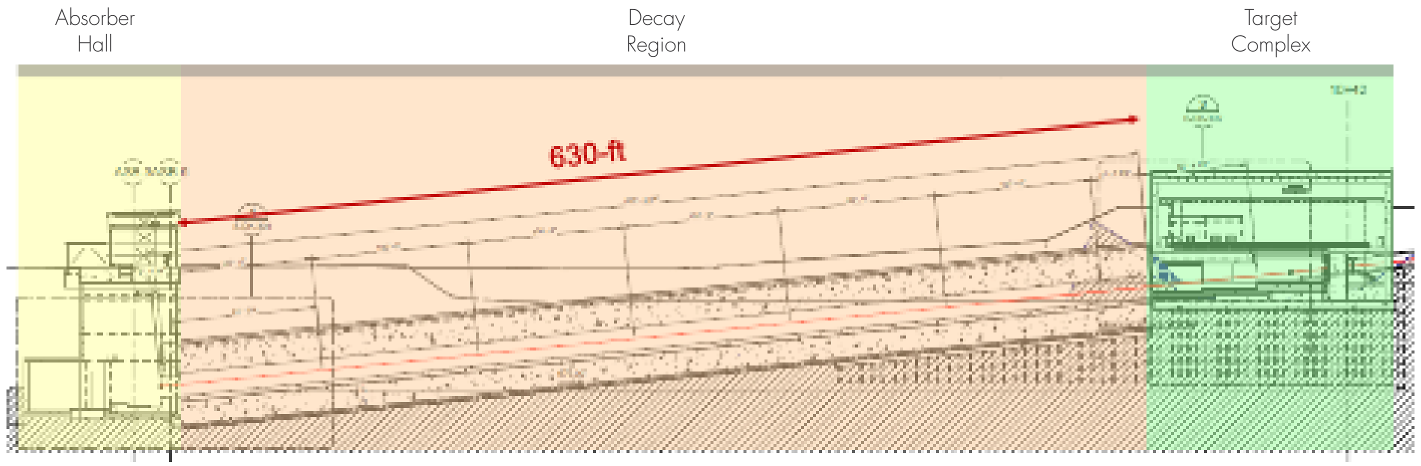

FIGURE 2. Overview of Decay Region

to a detection facility in an old mineshaft at Sanford Underground Research Facility in South Dakota, a facility that can also detect neutrinos hitting the earth from exploding stars.

After the graphite collision what is left behind has the potential to create some harmful biproducts such as tritium, or hydrogen-3, which needs to be kept out of the surrounding atmosphere, soil, and ground water. This occurs in the decay region slightly downstream from the target complex, which is 630-ft long concrete tunnel with 18 feet of concrete surrounding the beam line. Exiting the decay tunnel any leftover particles are absorbed downstream in the absorber hall.

The tunnel of the decay region houses an octagonal shielding concrete structure to provide shielding for the byproducts. This octagonal structure is over fifty feet tall and wide with 42,000 cubic yards of concrete, enough concrete to construct a baseball stadium. At the center of the tunnel is a double walled stainless steel pressure vessel charged with helium on the inside and a chilled flow of nitrogen gas within the annulus. The octagonal shielding concrete structure is surrounded by an access area to inspect the structure, the outer decay tunnel walls, and the surrounding soil. The octagonal shape of the shielding concrete was not always so octagonal. Starting off with small steps, Structural Integrity demonstrated advanced capabilities to model thermal structural behavior of mass concrete, while developing and expanding on existing capabilities. SI's positive impact on the early stages of the project earned us a larger role where we displayed additional capabilities to positively influence the design of the structure.

SI followed the design progression and answered some critical questions, such as:

1.) Will the decay region be within acceptable temperatures when subject to the extreme energy deposition from the decaying particles?
2.) What thermal expansion joints will be required to prevent cracking, and movement of the underground structures in a harmful way?
3.) How can we best optimize the reinforcement of such a massive structure?

SI answered these questions and more through expert analysis, expanding our capabilities through proprietary simulation ranging from earlier design concepts, construction stages, and up to including a 50-year design life of the structure.

Part One of this article will look at the influence our work had of the design of the massive structure and the benefits of "seeing the cracks" before they happen.

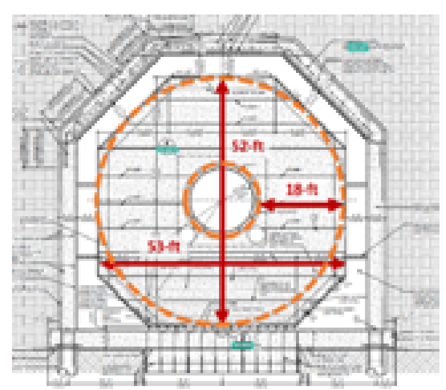

FIGURE 3. Typical Decay Region Tunnel Cross Section

ENERGY DEPOSITION AND COOLING THERMODYNAMICS

Concrete that gets too hot can vaporize the pore water and even break apart. The transfer of heat in concrete is a critical component of the analysis and is both added to the structure and removed. Thermal loading was provided by Fermilab in the form of volumetric energy deposition (EDEP) on the concrete and steel based on particle physics software simulation program MARS. The distribution of EDEP varies both radial outward from the beamline and compounded by its positioning along the length of the tunnel. SI would need to convert the distribution into a subroutine of distributed flux for use by the analysis program. The distribution was first translated for use in 2D analysis, expanded into 3D space, and then rotated in coordinate space to account for the slope of the beamline. With the EDEP adding heat to the system, chilled nitrogen is needed to remove heat.

A bit of "back-to-school" was needed to solve the thermodynamic problem. The heat transfer coefficient and temperatures of the nitrogen gas cooling system were calculated using classical methods on convection relationships in annular spaces. With the known EDEP into the concrete and steel, which dominates in regions closer to the center, it was decided as a design condition that all heat be taken by the nitrogen to obtain the outflow temperature of the nitrogen gas. The nitrogen temperature was calculated in 10m increments along the annular pressure vessel and at outflow based on an energy balance equation. The heat transfer coefficient was calculated using three different empirical relationships for Nusselt number utilizing the lower bound conservative estimate in the analysis. Our efforts created an accurate model in 3D space of the heat transfer into the shielding concrete. As a result of the nitrogen cooling system, we were able to keep concrete temperatures below

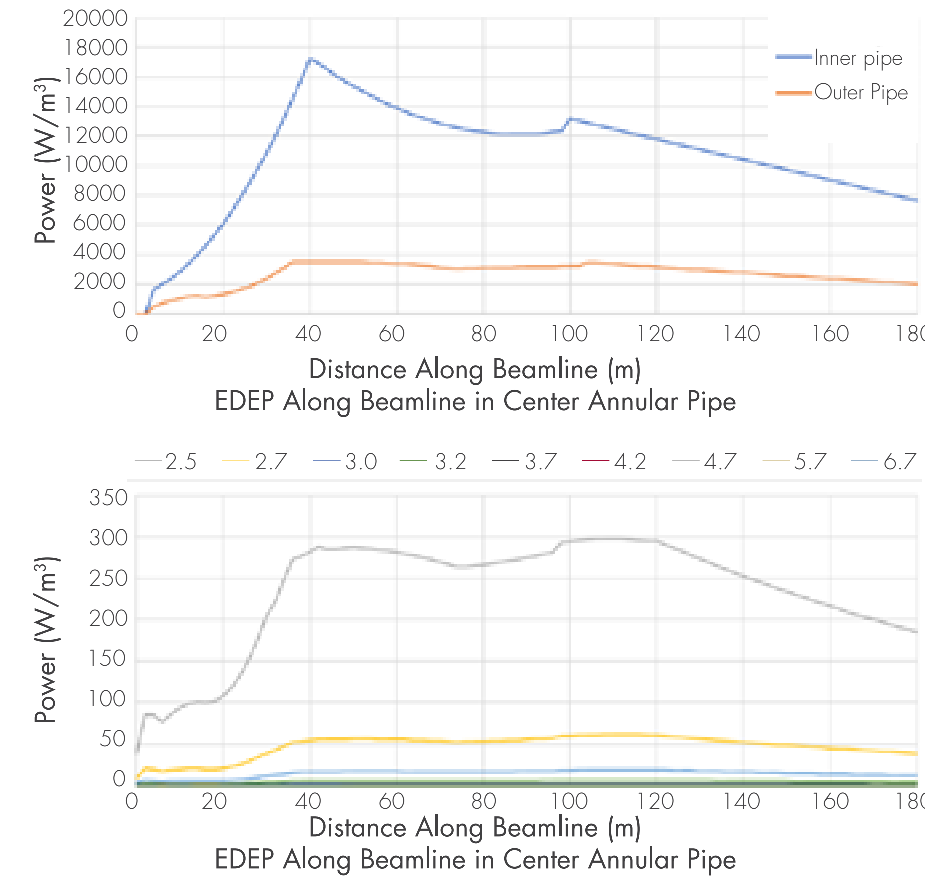

FIGURE 4. EDEP Axial and Radial Distribution along the Beamline

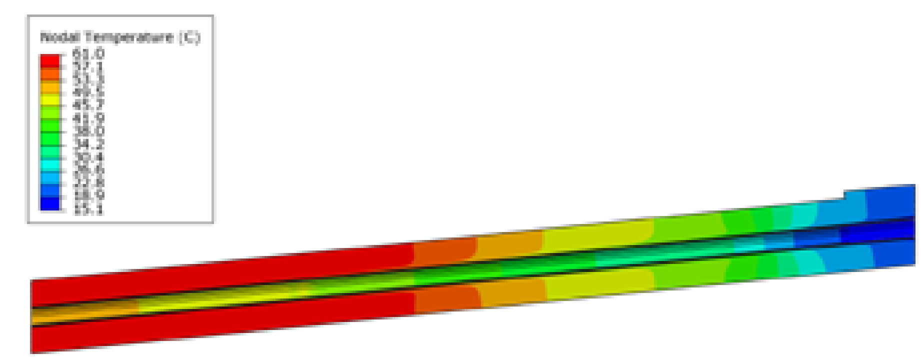

FIGURE 5. Accurate Thermal Distribution along the Decay Tunnel Shielding Concrete Structure.

the limit of 110 degrees Celsius. With the thermodynamic problem solved, SI progressed, coupling the solution to the mechanical stress model.

CONCRETE CAPABILITIES

If there is one thing concrete is guaranteed to do, it is to crack. SI's proprietary concrete constitutive model, ANACAP, is designed to predict concrete cracking and preform under various states of those cracks opening and closing. The behavior of concrete is highly nonlinear with low tensile strength, shear stiffness and strength that depend on crack widths, and plasticity compression. The main components of the concrete model utilized in the design phase analyses are tensile cracking, post-cracking shear performance, and compressive yielding when the compressive strength is reached. The use of the

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ANACAP concrete model has been validated and verified through 30 years of use and a key component for the nonlinear assessments.

INFLUENCE ON DESIGN

Accurate modeling of thermodynamics / thermal analysis, coupling with the mechanical model / stress analysis, and the capabilities of the nonlinear constitutive concrete model allow for the simulation of a full 3D model of the shielding concrete under full power operations. The design team sought to minimize the cracking of the structure, monitor elongations and other movements affecting the beam line, and design connections at the structure boundaries. SI coordinated with research and design teams to facilitate several cross-section iterations with different shapes and layers of shielding. Each design iteration was analyzed to demonstrate the benefits or consequences. An early iteration of the shield concrete cross-section was a stepped block shape. The corners of the stepped cross-section displayed the potential for cracking. SI addressed this potential design trait through influencing the development of the octagonal section shape. This optimization allows the design to minimize the amount of reinforcement needed to control cracking.

In addition to the cooling annulus at the center of the structure, there are the return ducts for the system to bring the nitrogen back to the target complex facility. The design initially used four return pipes spread out at four different corners. In one iteration the design team attempted to reduce the four return ducts to one larger return pipe to reduce the concrete volume required for shielding. The design iteration with one return duct was attempting to reduce costs by reducing the overall amount of concrete needed. Our calculations quickly identified unintended consequences. The asymmetrical shape was creating displacements along the transverse horizontal direction, pushing the beam alignment off-center by over an inch (~30 mm). The shape was quickly updated to be symmetric with two return pipes.

From room temperature to 60 degrees Celsius, concrete is going to expand. Traditional thermal breaks cannot be utilized in this structure to maintain continuity and provide shielding. The design needed to allow the structure to expand at the downstream end. Most of the structure is supported by rails where it was designed to freely slide at the bottom of the octagonal section during the expansion phase. A section of these rails needs to be fixed at the upstream end where it was designed to resist the gravity of the structure along the slope. SI provided valuable design influence with where the fixed rails were to be positioned as the thermal loading created immense stress at the location between the fixed boundary and sliding boundary. In the original position, SI's calculations identified a concentrated area of cracking. To minimize the amount of cracking and additional reinforcement needed, SI proposed moving the position of restraint towards the cool / upstream end of the tunnel.

How do you stop 42,000 cubic yards of concrete from expanding?

Answer: You Don't.

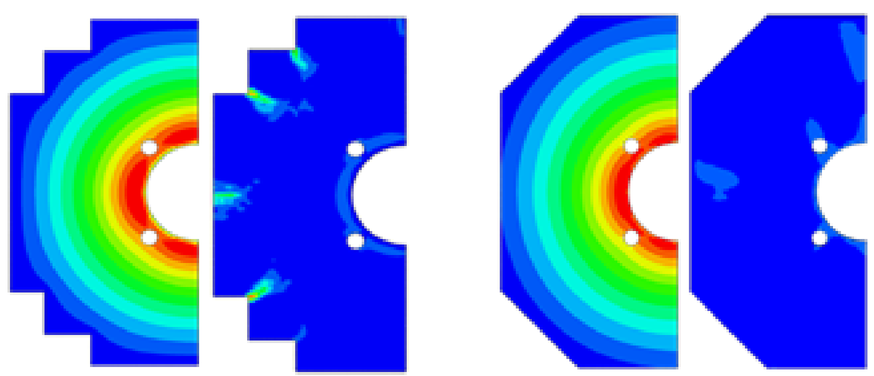

FIGURE 6. Stepped vs Octagonal Cross Section, Thermal Distributions and Concrete Strain (Cracking)

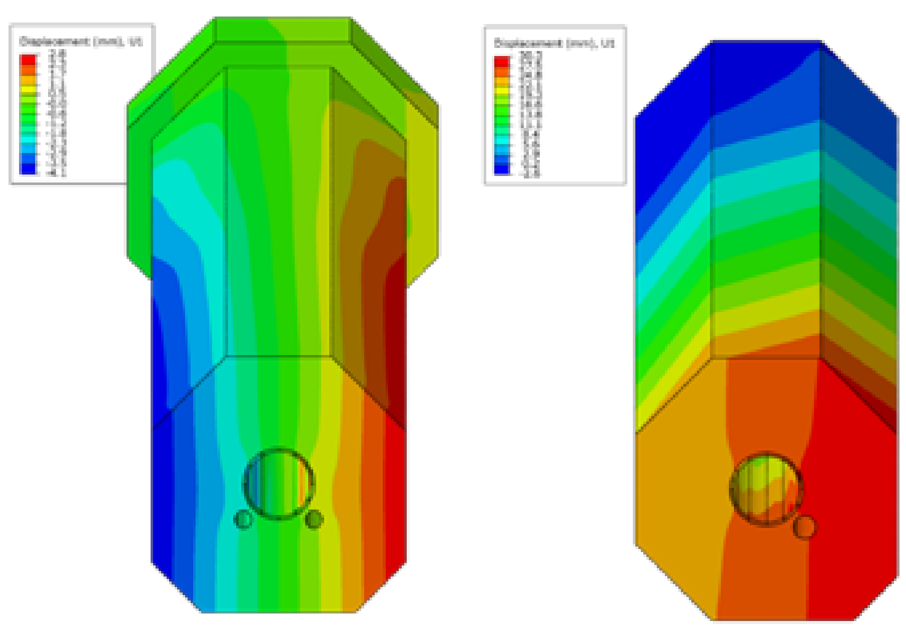

FIGURE 7. Lateral Displacements of Single Return Pipe and Dual Return Pipe

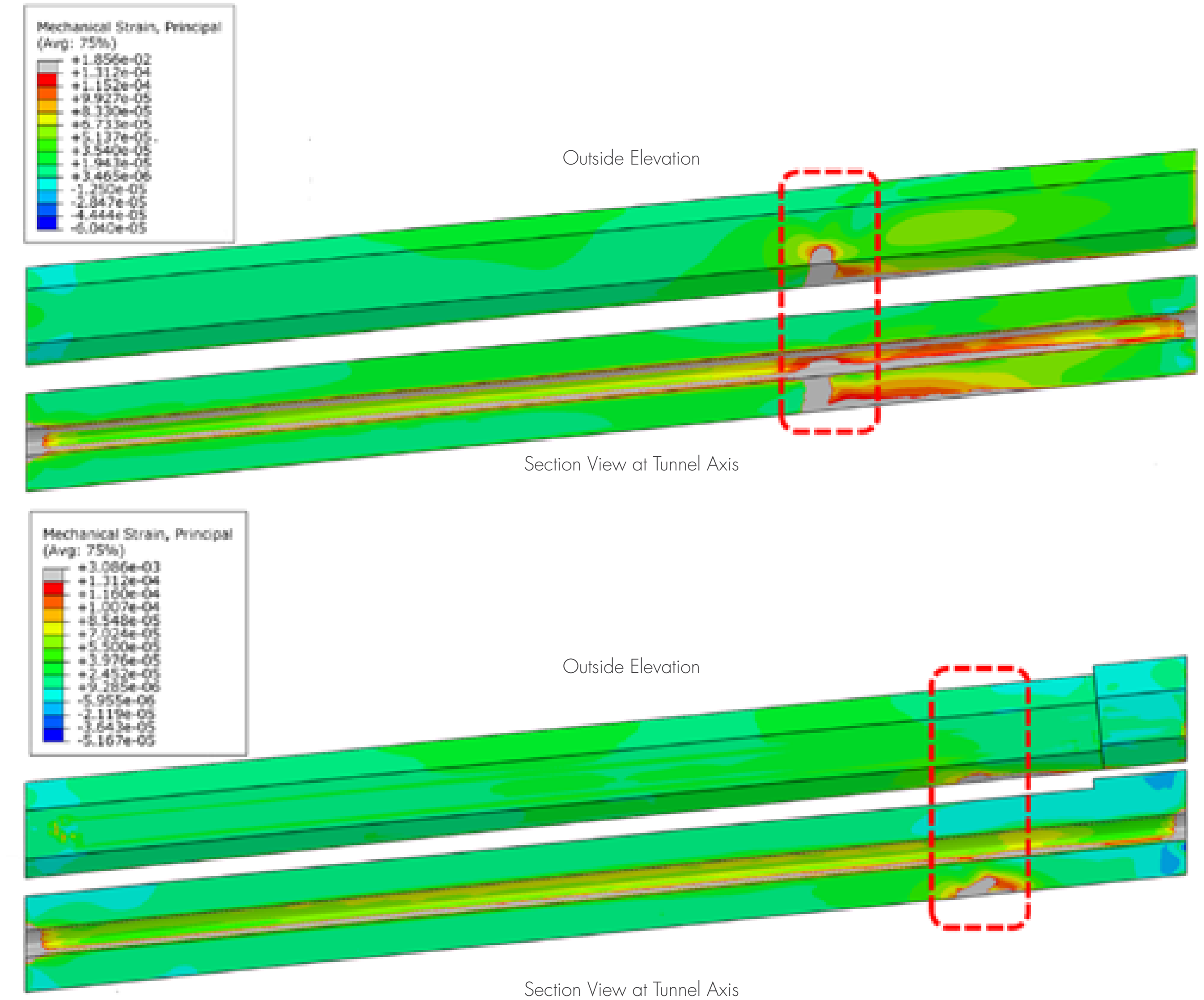

FIGURE 8. Effect of Fixed Rail Boundary Condition Position on Strain.

CONCLUSIONS

Structural Integrity successfully developed expanded capabilities to model thermodynamics for the energy deposition and nitrogen cooling system. SI used the capabilities of our concrete model to influence the structural design by "seeing the cracks" before they happen, making design adjustments, and reducing reliance on additional reinforcement. SI was able to give key insights for the concrete structure and potential cost savings through optimization.

Part Two of this article will look at the life of the structure form the day concrete is first poured to 30 years of power cycles. Delving into the future to see this structures test of time and monitoring methods to see if our predictions come true.

High Temperature Ultrasonic Thickness Monitoring

Technology Innovation - Thick Film Sensors

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The ability to continuously monitor component thickness at high temperatures has many benefits in the power generation industry, as well as many other industries. Most significantly, it enables condition-based inspection and maintenance, as opposed to schedule-based, which assists plant management with optimizing operations and maintenance budgets and streamlining outage schedules.

The ability to continuously monitor component thickness at high temperatures has many benefits in the power generation industry, as well as many other industries. Most significantly, it enables condition-based inspection and maintenance, as opposed to schedule-based, which assists plant management with optimizing operations and maintenance budgets and streamlining outage schedules. Furthermore, it can assist with the early identification of potential issues, which may be used to further optimize plant operations and provides ample time for contingency and repair planning.

FIGURE 1. Photograph of an ultrasonic thick-film array for monitoring wall-thickness over a critical area of a component.

Over the last several years, Structural Integrity has been working on the development of a real-time thickness monitoring technology that utilizes robust, unobtrusive, ultrasonic thick-film sensor technology that is enabling continuous operation at temperatures up to 800°F. Figure 1 shows a photograph of an installed ultrasonic thick-film array, illustrating the low-profile, surface-conforming nature of the sensor technology. The current version of this sensor technology has been demonstrated to operate continuously for over two years at temperatures up to 800°F, as seen in the plot in Figure 2.

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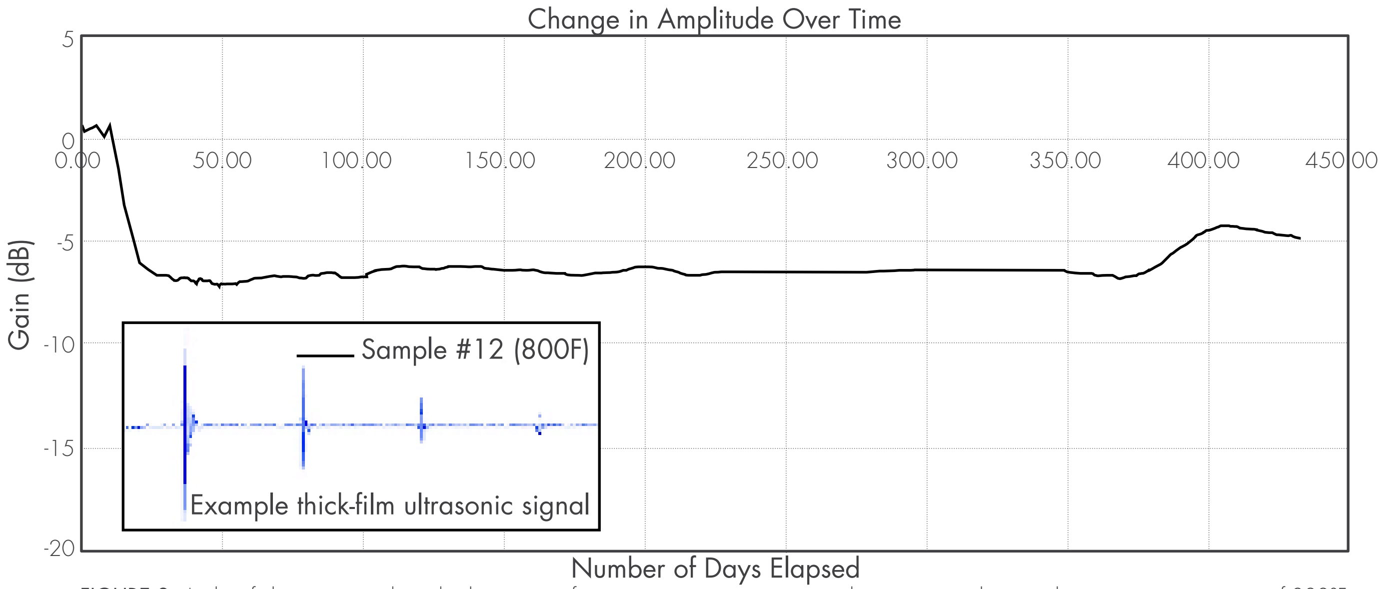

FIGURE 2. A plot of ultrasonic signal amplitude over time for a sensor operating continuously at an atmospheric and component temperature of 800°F.

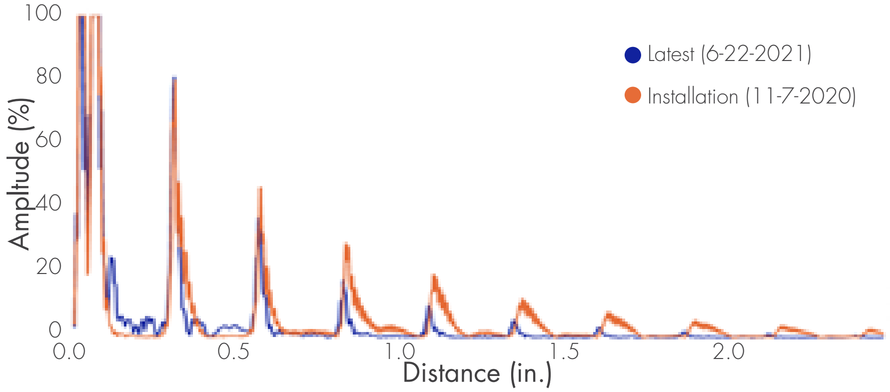

FIGURE 3. Ultrasonic waveforms acquired approximately 8 months apart showing 0.005 inches of wall loss at the sensor location over this period.

In addition to significant laboratory testing, the installation, performance, and longevity of Structural Integrity's thick-film ultrasonic sensor technology has been demonstrated in actual operating power plant conditions, as seen in the photograph in Figure 4, where the sensors have been installed on multiple high-temperature piping components that are susceptible to

Continued on next page

FIGURE 4. Photograph showing Structural Integrity's thick-film ultrasonic sensor technology installed on two high-temperature piping elbows that are susceptible to thinning from erosion.

wall thinning from erosion. In this application, the sensors are fabricated directly on the external surface of the pipe, covered with a protective coating, and then covered with the original piping insulation. Following installation, data can either be collected and transferred automatically using an installed data acquisition instrument, or a connection panel can be installed that permits users to periodically acquire data using a traditional off-the-shelf ultrasonic instrument.

Figure 3 shows two sets of ultrasonic data that were acquired approximately eight months apart at an operating power plant. The first data set was acquired at the time of sensor installation and the second data set was acquired after approximately eight months of typical cycling, with temperatures reaching up to ~500°F. Based on the observed change in the time-of-flight between the multiple backwall echoes observed in the signals, it is possible to determine that there has been approximately 0.005 inches of wall loss over the 8-month period. Accurately quantifying such as small loss in wall thickness can often provide meaningful insight into plant operations and processes, can provide an early indication of possible issues, and is only possible when using installed sensors.

Other potential applications of Structural Integrity's ultrasonic thick-film sensor technology include the following:

- Real-time thickness monitoring
  - Flow Accelerated Corrosion (FAC)
  - Erosion / Corrosion
- Crack Monitoring
  - Real-time PAUT
  - Full Matrix Capture
  - Critical Area Monitoring
- Other Applications
  - Bolt Monitoring
  - Guided Wave Monitoring

In addition to novel sensor technologies to generate data, Structural Integrity offers customizable asset integrity management solutions, such as PlantTrack™ , for storing and managing critical data. Many of these solutions are able to connect with plant historians to gather additional data that feed our engineering-based analytical algorithms, which assist in converting data into actionable information regarding plant assets. These algorithms are based on decades of engineering consulting and assessment experience in the power generation industry.

Reach out to one of our NDE experts to learn more about SI's cutting-edge thick-film UT technology.

Drone Inspections SI Expanded Capabilities

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Structural Integrity (SI) has recently added drones to our toolbox of inspection equipment. Using drones, inspectors are able to complete visual inspections safely and more efficiently. Applications of drones for visual inspections include plant and piping walkdowns, structural inspections and atmospheric corrosion monitoring (ACM) of exposed pipeline.

Pipe hanger walkdowns at fossil and combined cycle plants are part of a routine inspection process. During these inspections, the inspector is required to view and mark down pipe hanger positions and assess their condition. While some hangers provide easy access for the inspector, this is not always the case. Some of these may be located in elevated positions that require the plant to build out scaffolding, which not only increases the cost, but also can put the inspector at risk when working at elevation. With the use of drones, the inspector can fly up to the pipe hangers from a safe location and get a live high-resolution video feed from the camera mounted on the drone. Saving pictures and the video footage can also allow the inspector to go back and review the footage at a later time.

ACM is another example where drones have proven to be a useful tool. ACM inspections of outdoor above ground pipelines are typically done by walking down the pipeline and recording any signs of atmospheric corrosion. There are many occasions where the pipeline will be elevated or cross over rivers and railroads, requiring scaffolding or fall protection. By using a drone to fly along the pipeline, the inspection can be completed much more efficiently and safely. In situations where a GPS signal is available, such as outdoor pipeline inspections, the GPS coordinates can be saved with each photo. Custom SI-developed software can then automatically compile the acquired images and create a KML file to be viewed in Google Earth, allowing the client to get an overview of the inspection results.

Moving forward, SI plans to utilize these drones for more than just visual inspections. Possible applications could include using drones to perform ultrasonic thickness testing or Structural Integrity Pulsed Eddy Current (SIPEC™) examinations. All of SI's pilots in command hold valid FAA Part 107 certificates and pilot registered drones.

FIGURE 1. Drone image of a dent on an elevated section of pipeline

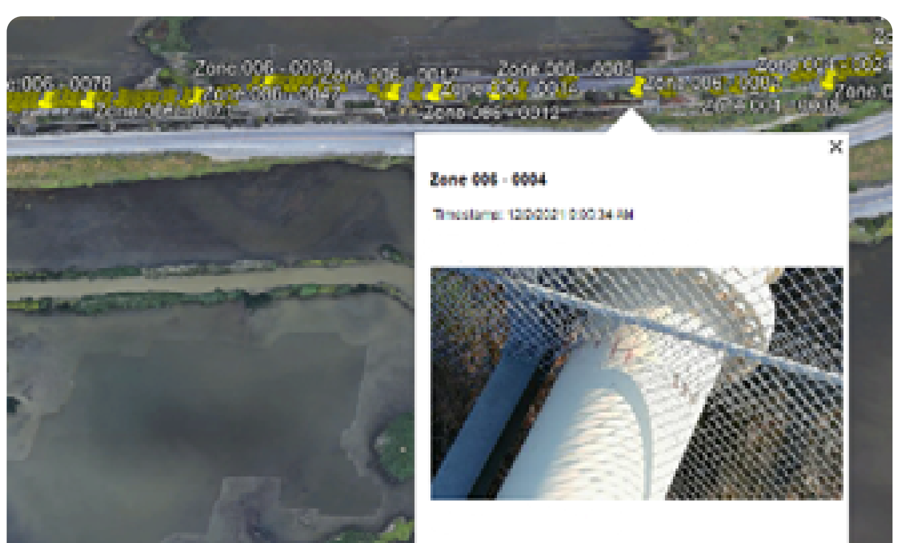

FIGURE 2. Google Earth view of image locations

Turbine Unit Trip and Event

Recovery Best Practices

When a unit trips or experiences an event, the site will incur costs associated with the loss in production, regulatory penalties, and, if applicable, outage scope, hardware replacement, and the purchase of make-up power. These costs can drive the priority of returning to service to quickly become the only priority.

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With the reduction in staffing at power plants over the past 2 decades, many traditionally routine engineering and maintenance tasks have fallen by the wayside. With limited resources, operations and engineering personnel must focus their time and efforts based on priority. Quite often, keeping a unit online or quickly returning a unit to service will take priority over continuous improvement actions such as investigations and root cause analysis.

When a unit trips or experiences an event, the site will incur costs associated with the loss in production, regulatory penalties, and, if applicable, outage scope, hardware replacement, and the purchase of make-up power. These costs can drive the priority of returning to service to quickly become the only priority. Unfortunately, the review of event operational data, event precursors, and the collecting of evidence through the unit disassembly very often fall below the priority of returning to service. Collecting or re-creating evidence after the fact is nearly impossible. This lack of priority often results in a lack of understanding of the root cause of the trip or event.

Within large, complex plants and turbomachinery, trips or minor events are common, but are rarely isolated, one-off events. Many trips and events are repetitive in nature, and worse, are early indications of a more serious event to come. While the cost of delays in returning to service may be high, the cost of not solving the root cause may be orders of magnitude higher, particularly if a failure event happens a second time.

Focusing on unit trips, best practices include:

- Hold regular, cross functional trip reviews.
- If available, consider holding reviews across similar sites within a parent company.
  - Utilize knowledge and solutions that may already have been developed.
- Trend trip events and frequency over a 1-to-3-year period.
  - Measure the success of prior projects based on the reduction of occurrences or elimination over a multi-year period.
  - Trips may be seasonal in nature and re-occurrence may span timeframes greater than one year.
- Review each trip as a near miss and assess potential consequences that may not have occurred this time.
- Consider including trip investigation in site or corporate level procedures and celebrate successes.

Focusing on unit events, the cost of an event requiring an outage and hardware replacement, not including make-up power purchase, can very quickly escalate to millions of dollars. Compare that cost to the cost of a dedicated, independent resource for the duration of time required to perform a comprehensive investigation. Also, consider the cost of the investigation versus the cost of reoccurrence, or a similar event with more serious consequence. The cost of the resource and investigation will almost always be in the noise of the overall cost. Best practices include:

- In nearly all cases, site and outage resources will be dedicated to the speedy rehabilitation of the unit.
  - Critical evidence is often lost or destroyed, unintentionally, based on the need to return to service quickly.
  - A dedicated, independent resource provides the best option to ensure that useful evidence is collected.
- Assign a dedicated, independent resource to collect and review data and findings.
  - If a site resource is not available, borrow from a sister site or corporate team, ideally someone with an outside perspective and not necessarily an expert in the field.
  - Consider an external independent resource such as an industry consultant.
  - It will likely require a team to complete the overall root cause analysis, however, the likelihood of success will be much greater with facts and details being collected by a dedicated resource.
- Initial steps as a dedicated, independent resource:
  - Ensure a controller and DCS data and alarm logs backup is completed before they time out.
  - Interview individuals that were on site at the time of the event and / or in the days prior.
  - There is no such thing as too many pictures. It is common to find a critical link or detail in the background of a picture taken for another reason.
  - Clearly articulate hold points at which the independent resource will require inspections or data collection through the disassembly process.
  - Collect and preserve samples and evidence.
- Where available, utilize other fleet assets to enable a detailed causal analysis with corrective and preventative actions.
  - Demonstrating a commitment to fleet risk reduction can minimize impacts with regulators and insurers.
- Once an event occurs, those limited resources will be fully occupied. Creating a plan at this point is too late.
  - Discuss including the cost of an investigation into an event insurance claim with site insurers and what their expectations would be to cover the cost.
  - Maintain a list of resources, internal and external, to call upon as dedicated, independent resources.

Identifying the root cause of an event might be cumbersome, but far less cumbersome than dealing with the same type of event on a recurring basis.

Structural Integrity has team members and laboratory facilities available to support event investigations and to act as independent consultants on an emergent basis.

Deaerator Tank Failure

Effective Assessment Techniques


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Recently, Structural Integrity Associates (SI) helped a client with a leaking deaerator tank (DA tank). DA tanks are traditionally used to remove dissolved gasses from liquids. The client's DA tank in particular is used to remove dissolved oxygen in feedwater for steam-generating boilers; this is done because dissolved oxygen can create a corrosive environment within the boiler as it will attach to the metal components, creating oxides. The DA tank protects the boiler from these corrosive gasses, however, to the DA tank's detriment, not much protects it from those same gasses. Repairs on DA tanks are common and additionally it is not uncommon for those repairs to continue to experience problems.

The DA tank being investigated for leaking in this investigation had an entire shell segment, various full thickness patch plates, and a head replaced in 2018 due to wall thinning caused by flow-accelerated corrosion (FAC). The current leak was caused by cracking of a girth and longitudinal seam weld in a mismatched repair patch. The failure prompted inspection, stress analysis, and repair consulting by SI. The following reveals the steps taken to repair the failed DA tank. Initial visual inspection of the leaking DA tank indicated that the problematic repair patch had significant radial mismatch relative to the tank shell to which it was welded and grossly oversized weld layers resulting in high tensile shrinking stresses. The mismatch resulted in significant bending at the weld line and the excessive weaving of the weld layers led to tensile forces acting on the weld imperfections at the toe of the welds. Due to the visual finding, 3D scanning was performed to better understand the magnitude of the mismatch.

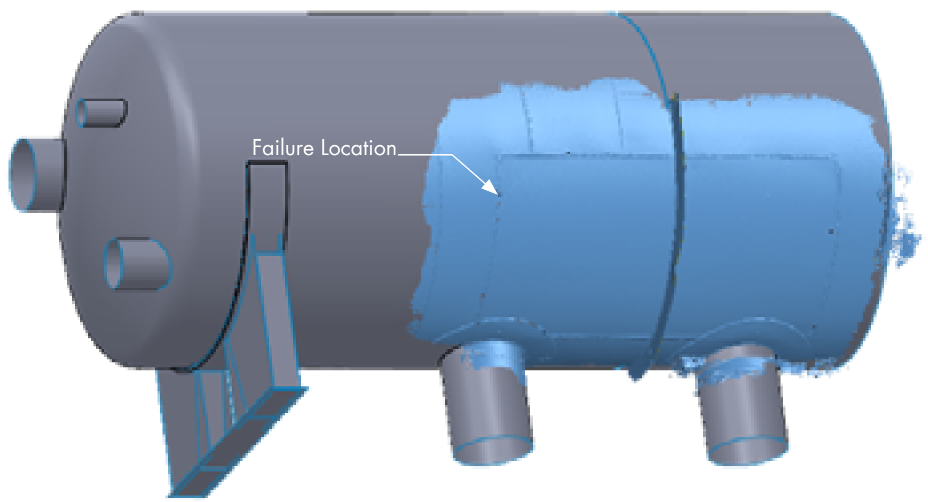

FIGURE 1. Segment of DA Tank and 3D Scan Area

The 3D scanner works by projecting structured light with a specific pattern onto the surface while cameras measure the deformation across that surface. The 3D scan data was then further processed with Solidworks®, a 3D computer aided design (CAD) software. Figure 1 shows the extents of the scan data. As initially suspected, it was found that there were areas of substantial mismatch between the patch and tank shell. A deviation analysis of the scan helped determine the areas of maximum deviation between the repair patch and tank shell (see Figure 2, worst locations are highlighted in magenta). There was approximately a quarter to a half inch of mismatch in the weld seams at the location which the leak occurred. This location's scan data and its substantial mismatch are shown in Figure 3.

These findings prompted a finite element stress analysis (FEA) of the DA tank to provide better understanding of how the mismatched areas react to the loadings and thermal conditions of the DA tank. The model includes a simplified version of the repair patch, which incorporates the mismatch deviations determined from the 3D scan. As suspected, numerous locations had stress concentrations that exceeded the allowable bending stress for the materials of construction. The stress concentrations between the repair patch and the base material are a product of the bending induced between the two as they try to "straighten" out when the tank is pressurized. The excessive stress concentrations, weld imperfections, and corrosive environment were a recipe for crack growth and subsequent failure of the weld.

Ultimately, the dimensional and stress analyses performed on the DA tank helped determine and understand the problematic mismatch areas. This work determined that elevated local stresses caused by mismatch between the repair patch and the tank shell were sufficient to induce cracking in the patch seam welds as the stresses in these locations exceeded the allowable ASME bending stresses.

SI was also able to provide nondestructive testing, welding expertise, and oversight during the excavation of the cracking and mismatched welds to ensure that it was rewelded properly. A significant amount of weld around the patch required removal to allow for in-situ straightening of the plate for proper alignment with the shell. Due to the poor weld quality during the initial installation of the patch a modified joint design was recommended by SI to eliminate the existing heat affected zones and restore the base metal and weld deposit reducing the excessive tensile stresses and providing a high-quality joint. The weld consulting ensured strict adherence to the modified joint design and elimination of weld flaws that act as crack initiation sites. Additional flaws were detected on both the outside and inside surfaces of the previous repair which led to additional cracking at locations other than the leak, which would have eventually caused other leak sites. These areas were addressed during this project reducing the probability of future leaks. These additional flaw sites highlight the importance of having qualified NDE technicians and an experienced welding consultants onsite during this type of repair.

DA tanks are notorious for FAC wall thinning, cracking, and requiring repairs. This project demonstrated SI's ability to work with a multidisciplinary approach including nondestructive evaluation (NDE), analytical stress analysis, and welding expertise, to determine the cause of the cracking in the DA tank and provide the oversight resources to ensure the repair was done properly. If you are experiencing a similar situation at your facility, SI would be happy to provide consulting services to assist you in a proper repair of your critical components.

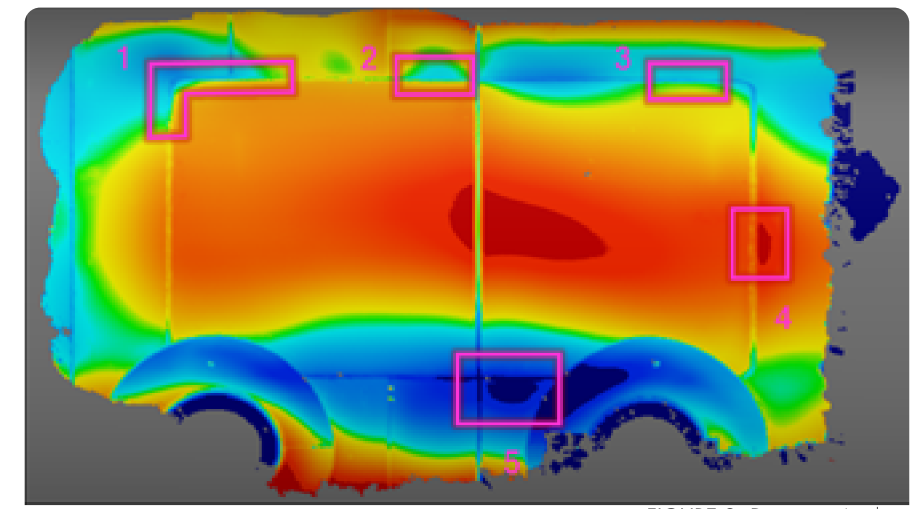

FIGURE 2. Deviation Analysis

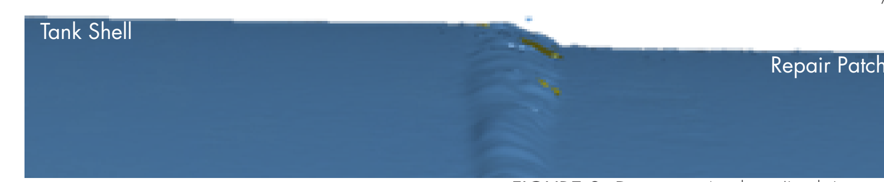

FIGURE 3. Deviation Analysis (Leak Location)

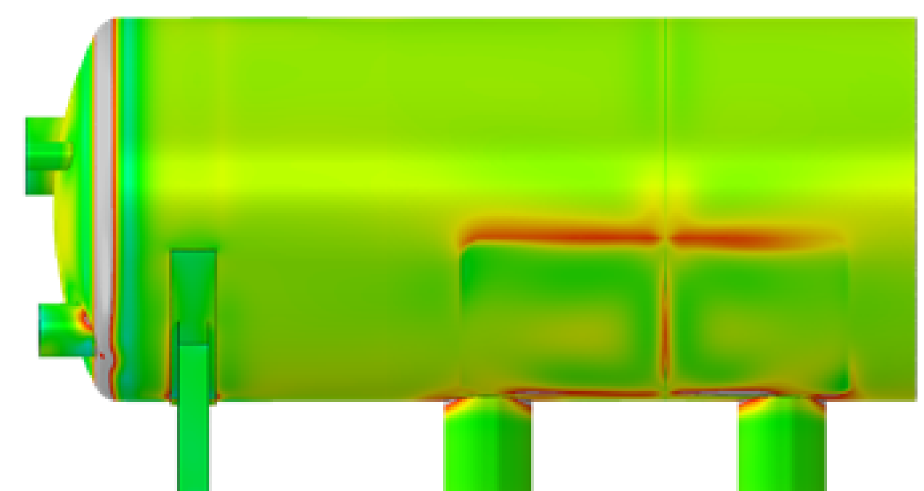

FIGURE 4. Finite Element (FE) Model Stress Results

Combustion Turbine Compressor Hygiene

Component Longevity

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INTRODUCTION

An industrial combustion turbine can ingest over 1000lbs of air per hour of operation. Entrained within the air is a spectrum of mineral, salt, moisture, and VOC, and other compounds that are present in the local atmosphere. Locally high concentrations of potentially corrosive species may also be present due to surrounding industries or even effluent from the power plant itself, such as cooling tower drift, evaporation cooler deposits, or water treatment effluent.

In addition to disrupting the flow path area of the compressor blades and vanes, with a consequential drop in compressor efficiency, these contaminants can also serve as sites for under-deposit corrosion cells that have implications for component life as well as risk for catastrophic failures. Compressor waterwashing with detergents has been utilized with some success by utilities as a method for mitigating the effects of deposit accumulation. Nevertheless, tenacious deposits can accumulate over time. The presence of moisture in the deposit can also result in activation of a corrosion cell that can corrode the typical stainless steels used for blade and vane construction. Higher strength PH stainless steel blades and vanes suffer a larger loss in fatigue endurance limit from pitting, and tend to suffer more airfoil liberations due to cracking initiated at pitting.

On forward compressor blades and vanes, qualified inspectors have also observed combined effects of leading edge erosion and pitting. The erosion is typically the result of on-line water washing. The roughness of the eroded leading edge is now an ideal area for compressor deposits to become deeply embedded. Additionally, it serves as multiple stress concentrations for fatigue crack initiation.

The fall in compressor efficiency, the irreversible damage due to erosion and corrosion pitting, and the risk of catastrophic damage due to fracture initiation at the affected areas, all suggest that O&M staff need to have a strategy to mitigate compressor deposit accumulation, as well as erosion channeling. Additionally, the strategy should also consider the scenario where some deposit accumulation is unavoidable and how to reduce the activation of these deposits. Consideration should also be given to units that have a history of blade failures due to a design limitations that makes them susceptible to corrosion fatigue cracking. In such cases, the unit has a low tolerance to the presence of corrosion pitting for crack initiation.

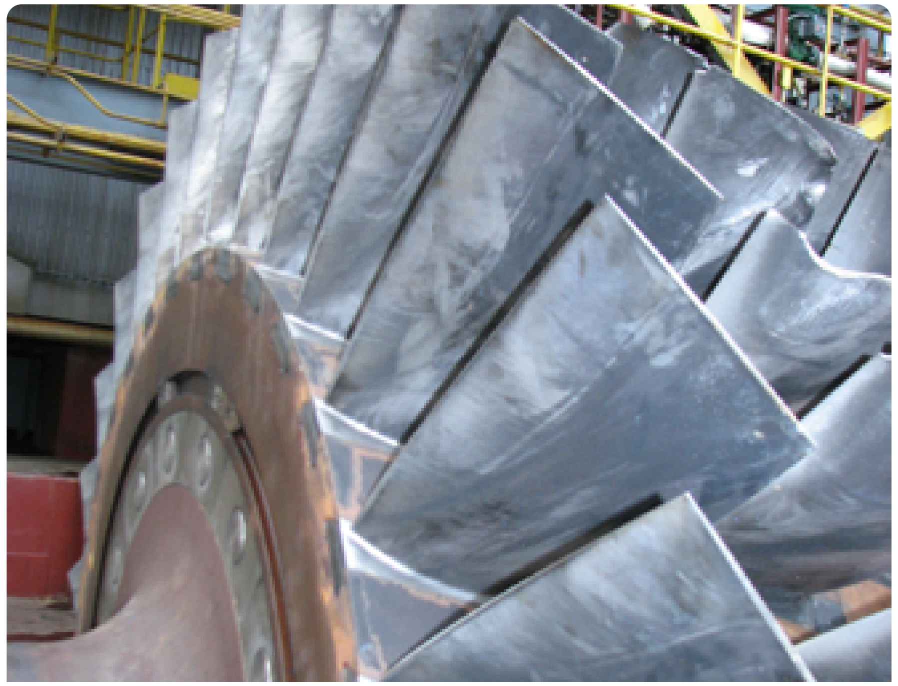

FIGURE 1. Compressor rotor inlet with fouling deposits

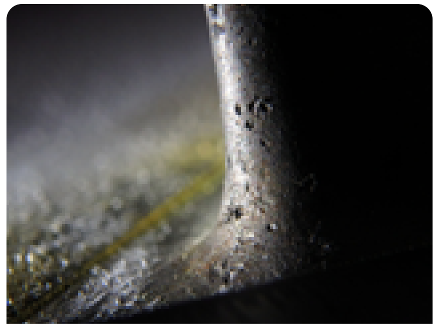

FIGURE 2. Forward compressor blade with leading edge pitting

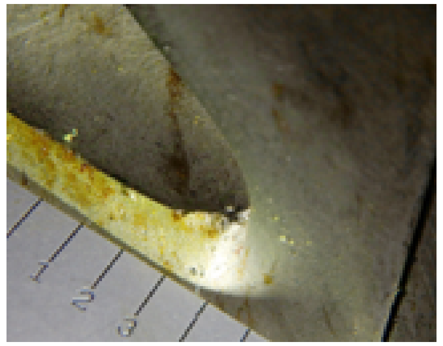

FIGURE 3. Fractured forward compressor blade with leading edge pitting at the origin

TYPICAL SOURCES OF CONTAMINATION - LAND

Local geology and soil can contain large amounts of calcium, iron, magnesium, aluminum potassium, sodium, phosphorus, sulfur, as well as other less common species, including chlorides where the dry land used to be a sea bed. These elements are usually present as a compound, such as a mineral oxide or a salt, but may also be bound with organic material in the soil. Even with reasonably high efficiency filtration that removes 99.7% of the particulates within a given particle size range, the remaining 0.3% contamination multiplied by 1000lbs / hr of influent air results in a high rate of deposit accumulation. Deposits accumulated on airfoil surfaces can then liberate ionic species due to the absorption of moisture, thus creating a corrosion cell. Chlorides due to ubiquitous salts will rapidly corrode (pit) any and all of the stainless steels used in gas turbine compressors, with only partial mitigation by coatings. The only class of compressor materials reasonably immune to chloride or under deposit corrosion is the titanium alloy blades and vanes used in flight turbines and some aeroderivative units. Sulfur containing compounds are also commonly found on the airfoils of compressor blades and vanes, particularly in regions with heavy industry and refining. Sulfur containing compounds can also be extracted and diverted to the hot gas path cooling channels of downstream components, and greatly accelerate hot corrosion in the absence of moisture.

ATMOSPHERE

The local quality of air entering the compressor is somewhat variable, and also dependent on geographic location. Coastal regions have an obvious problem with humid, chloride laden atmosphere. This particular environment is especially vulnerable to chloride pitting. Special inlet ducting and tailored filtration may provide some level of protection.

Local environments due to the proximity of inlets relative to cooling towers and the use of sodium hypochlorite for microbial control of cooling tower water can result in a chloride-laden influent to the unit. In this case the solution may be as simple as using a non-chloride based biocide for microbial control. In some cases the corrodents can come from non-typical activities at the plant, such as excursions of acid vapors from the water treatment facilities (sulfuric acid or hydrochloric acid).

Proximity to local industry, such as steel mills, coal or lignite fired boilers, oil production or refineries can result in a large influent concentration of sulfur bearing compounds. Sulfur bearing compounds, when incorporated into a deposit layer, can accelerate under-deposit corrosion and pitting, as well as aforementioned hot corrosion of downstream turbine components.

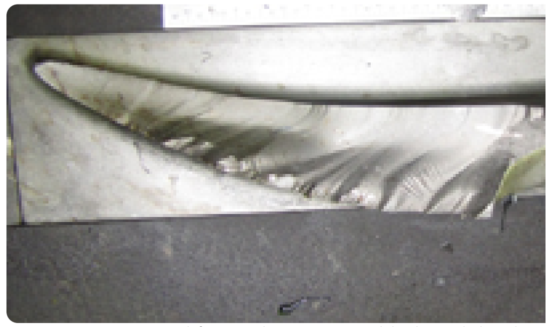

FIGURE 4. Fractured forward compressor blade with leading edge erosion at the origin

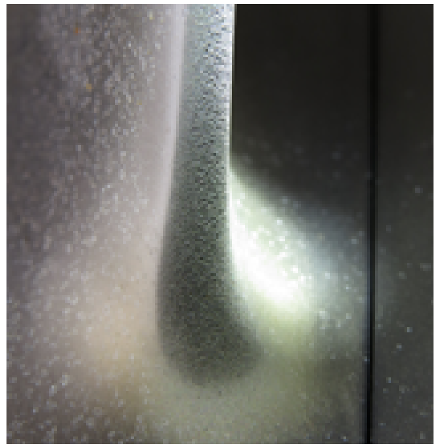

FIGURE 5. Forward compressor blade with leading edge erosion at platform radius

WATER

Water source used for compressor washing (online and offline), as well as water used for power augmentation (misting, evaporative cooling, etc) should ideally be demineralized

Continued on next page

quality or better. The use of city water or another source of hard water is generally discouraged. Online water washing with a hard water source can result in increased deposit accumulation at and beyond the phase transition area (stage 2-5 typically) where the water boils to vapor and the dissolved minerals will deposit onto the blade / vane surfaces. Power augmentation by closed loop chiller systems also affords the opportunity for contamination due to leaks in the chilled fluid. These fluids can have variable water quality as well as chemicals added to the chiller loop. Non volatile constituents of the chilled water may leave deposits in a similar fashion as hard water. Evaporative cooling with hard water will result in mineral shedding that can accumulate downstream. As mentioned, on-line water washing will often cause leading edge erosion channeling, and more severely if the droplet size is not controlled, or leaking occurs during operation.

HISTORICAL CONTAMINANTS OBSERVED IN COMPRESSOR DEPOSITS

Over the course of many years, we have been privileged to sample the deposits laden on blades and vanes from gas turbine units in many parts of the world. A pattern of contaminants (the usual suspects) has been observed, with some exceptions. The deposits observed are biased largely by one of the dominating contributors: Coastal conditions, land conditions, or local plant and industrial environment (neighboring industry or locally produced effluent).

Energy Dispersive Spectroscopy (EDS) provides qualitative elemental analysis of materials under scanning electron microscopy (SEM) examination based on the characteristic energies of x-rays produced by the electron beam striking a deposit sample. The relative concentrations of the identified elements are determined using semiquantitative, standardless quantification (SQ) software. This information can be used to tailor the filtration system and media, as well as the detergents used in compressor washing. It may also provide leverage for high level dialog with the local regulators and emitting sources.

FIGURE 6. Forward compressor blade with leading edge erosion at airfoil mid span

CONCLUSIONS

The corrosion pitting on the compressor blades and vanes is almost always the result of under-deposit corrosion aggravated by the presence of corrosive species in the deposit. The corrosive species are often sulfur and chlorine-containing compounds, but pitting can also occur from simply the presence of oxygen under the deposit (oxygen pitting). The pitting is proof of corrosive deposits, and trace amounts of corrosive species identified by EDS at the bottom interface of the pits identifies the active corrodents so that treatment can be fine-tuned for that species.

The source of the corrodents can be local to the plant (cooling tower drift), in the soil, from the atmosphere (coastal chlorides) or from local industry (burning lignite or low grade coal, and / or oil and gas production). In some cases the corrodents can come from non-typical activities at the plant, such as the use of sodium hypochlorite (bleach) for biological control, or excursions of acid vapors from the water treatment facilities (sulfuric acid or hydrochloric acid). Plant operations can identify, address and mitigate the local sources.

Starts-based units, or peakers, also have life-limiting pitting that is difficult to understand without considering the effect of off-line corrosion. For units operating in cycling duty, a substantial amount of time is spent in idle mode. During idle periods, the unit is normally stationary or on turning gear for some daily period. After the rotor is ambiently cooled during the nightly lows, the rotor will retain much of the lower temperature relative to the increasing ambient temperature and humidity during the day. As a result the rotor will sweat like cold drink on a warm day, and the deposits on the blades and vanes will be similarly affected. This is a common mechanism for deposit activation and corrosion that seems to be aggravated by the new paradigm of unit cycling. These are the periods where corrosive deposits combined with moisture will create conditions ideal for pitting, particularly if the airfoil deposits contain a substantial concentration of sulfur and chlorine-containing compounds.

MITIGATION

Units may be waterwashed online each day when operated and the ambient temperature is greater than about 50°F. Offline water washing may be performed prior to performance testing or to restore lost capacity. In both cases

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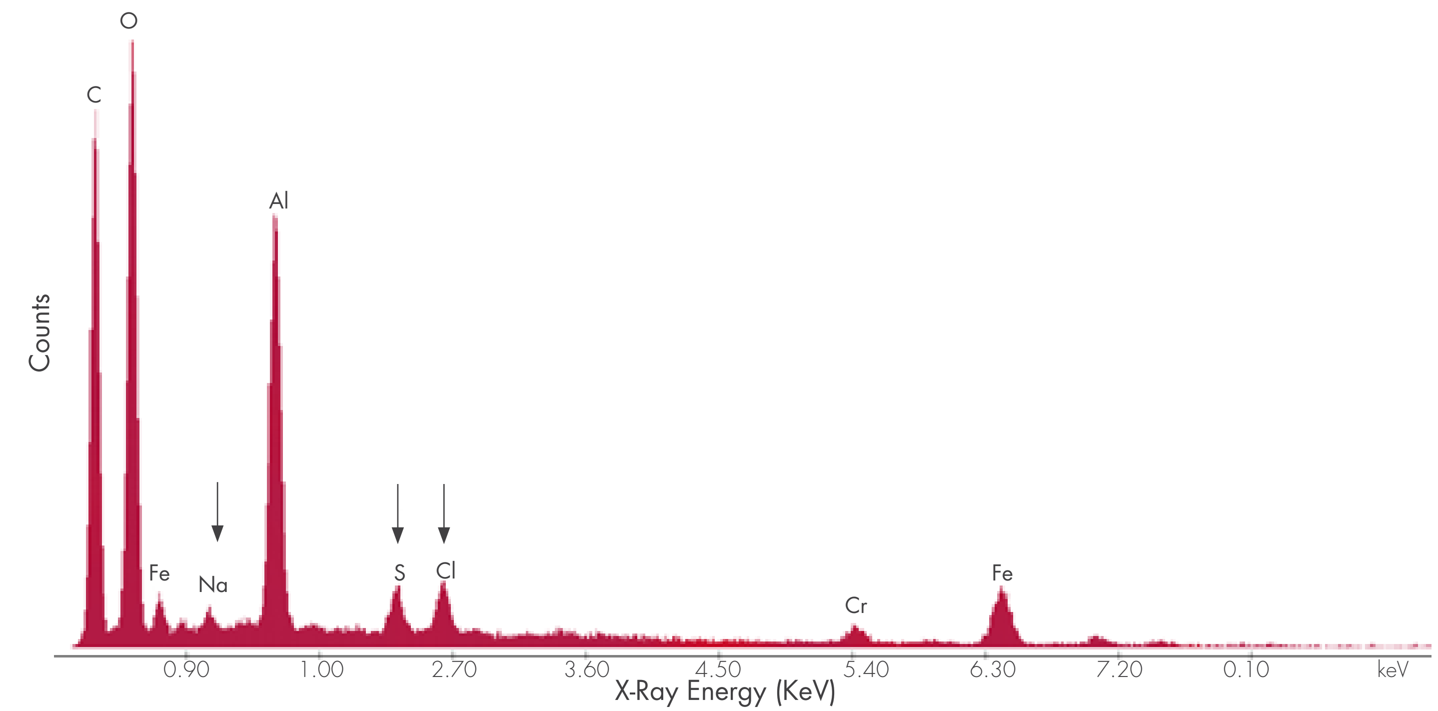

FIGURE 7. EDS Spectrum of compressor fouling deposits. Chlorides, sulfur deposits, and sodium deposits can be corrosive to stainless steels.

the water washing is performed to provide performance benefits and also to prevent the accumulation of corrosive deposits. However, performing an online waterwash prior to operation does not remove the deposits accumulated during the subsequent operation cycle, nor does it remove much deposit beyond the second stage due to phase transition from liquid to vapor. Moreover, if the subsequent operation cycle is followed by a long idle period in humid weather, the deposits can absorb the ambient moisture and activate the corrodents. Off-line washes must be performed with demineralized water and a cleaning solution tailored to the deposits. Proper rinses with conductivity measurements taken at the drain ports are advised. Offline water washing is much more effective at removing compressor deposit accumulation, but proper drying is necessary to prevent pitting under remaining, tenacious deposits.

Another aspect of the operation that can affect the compressor deposits and moisture is proper sealing of the inlet filter house. All seams should be sealed with a weatherproof material and the fitment surfaces should be in good condition. Water leaks from the roof or any other area that causes standing water should be addressed. Additionally, corroded surfaces should be prepped and painted to stop the corrosion. Any bolts, nuts, and screws should be inspected for significant corrosion and potential loss of material that can become foreign object damage.

From a mitigation standpoint, two aspects must be addressed to reduce the susceptibility to pitting. First, the accumulation of deposits must be reduced. This may be achieved by higher efficiency filtration media (such as HEPA and hydrophobic Gore® Filters) and more aggressive offline water washing with a cleaning solution tailored to the deposits. Second, the presence of unwanted water must be reduced. Waterwashing should be followed by operation to ensure all moisture is evaporated. Water repelling filtration (such as Gore® filtration media) may reduce some of the water ingestion during wet weather, and may also prevent some of the influent from cooling tower drift (Gore® filtration medial is quite expensive, so a cost-benefit analysis may be require do to justify the additional expense). Long idle or layup periods should be combined with closure of the bellmouth and with a dry air source (heater or dehumidifier) to ensure that corrosive deposits are not activated. Mist eliminators and auto-close stack dampers are also beneficial, and should have some effect on reducing the ingress of moisture into the combustion turbine unit.

A detailed unit inspection may be advised, during which time deposit samples can be collected from the pre-filters, conical filters, and forward compressor blades / vanes / IGVs for corrosive species survey, as well as establishing the efficacy of the current filtration system. At this time, the severity of any pitting can also be documented. Additionally, mold replication can be performed on the LE of the forward compressor blades to gauge the severity of erosion channeling, which is often governed by OEM technical letters or service bulletins. A survey of the inlet filter house is also advised, where potential points of uncontrolled ingress can be identified. Additionally, the structure can be mapped for corrosion, cracked or damaged structures, and potential fastener liberation.

Optical Microscopy

Applications and Benefits

In the world of metallurgical failure analysis, areas of interest on broken parts can be colorful or drab, three-dimensional or flat, and most importantly, very big or very small. A big part of failure analysis work is telling the story, explaining the failure mode, or in some cases, showing that critical piece of evidence that explains why a metal component has failed. From wide-angled lenses to extremely high magnification scanning electron microscope imagery, documentation of failed components is a big part of the presentation.

In this edition of Structural Integrity's Lab Corner, we wanted to provide some interesting content related to that middle-of-the-road region of magnification; closer than macro-photography but farther away than the 100X to 5000X magnifications that cover most of the applications requiring scanning electron microscopy. In other words, the comfortable world of optical microscopy, where colors, shapes, and even surface textures are part of the story. To do this, we've chosen some images that show the usefulness of quality optical microscopic documentation. Each of the provided examples include a brief description along with specific comments on the benefits of optical microscopy for that project, where applicable.

FIGURE 1. Two- and three-dimensional color images of an aluminum annode plate showing light-colored deposits that have caused uneven wastage. The 3D image shows the extent of material removal in locations where deposits are not present. Normal wastage in this application should be uniform.

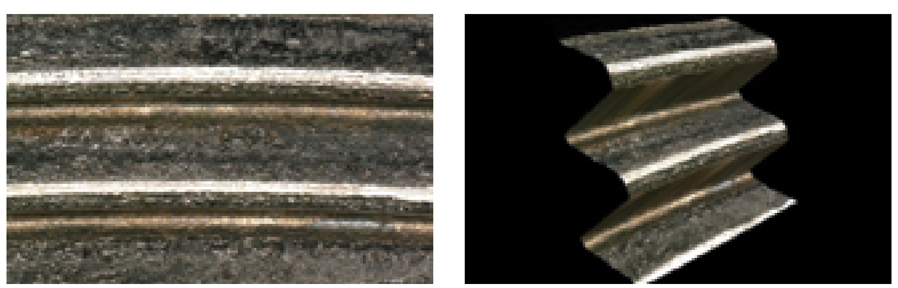

FIGURE 2. Two- and three-dimensional color images showing fastener thread flank damage and a crack origin near the root of the upper thread. The 3D image shows that the crack origin is located on the thread flank rather than at the deepest part of the thread root.

FIGURE 3. Two- and three-dimensional images of a copper heat exchanger tube that has been damaged from under-deposit corrosion (UDC). The image at left shows the typical appearance of the ID deposits. The center image shows a region of damage surrounding a pinhole leak. The 3D image provides an idea of the depth of internal corrosion in the tube.

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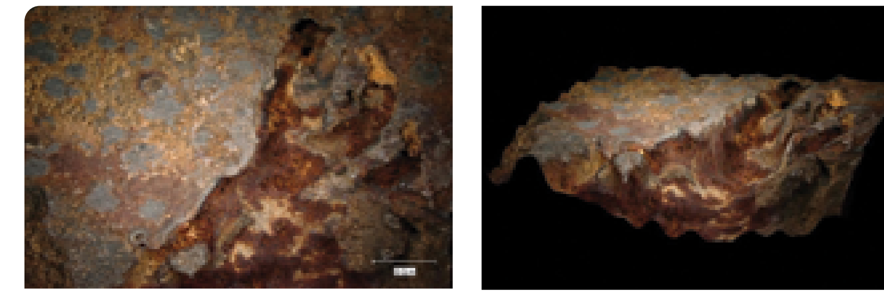

FIGURE 4. Two- and three-dimensional images of a region of damage on an internal surface of a feedwater pump. The image at left shows the appearance of brownish deposits found within the corroded region of the pump surface. The 3D image provides an indication of the depth and shape of the corrosion damaged region.

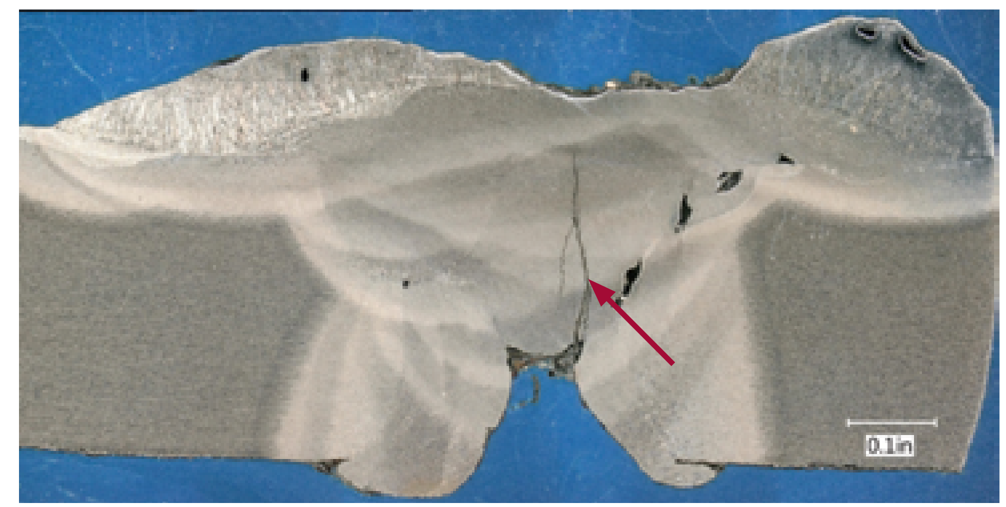

FIGURE 5. Two dimensional stitched image of a weld cross section showing cracking emanating from a shallow weld root. Porosity is also visible in multiple locations in the weld.

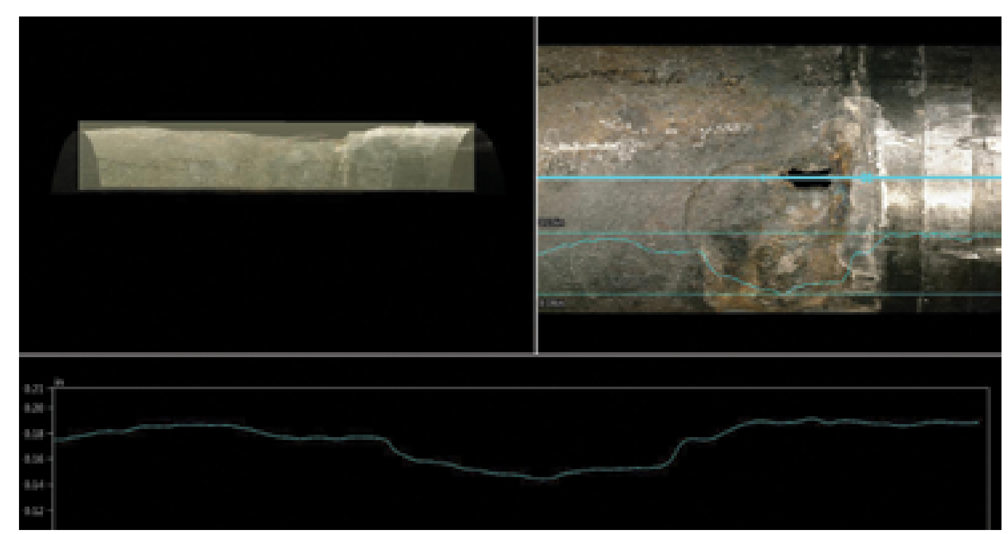

FIGURE 6. Images of a region of damage on the exterior of a heat exchanger tube where wastage has occurred near the tube sheet. The upper right image is a view of the leak location with an overlay of lines showing the position where the surface profile was documented as well as the depth profile (overlaid and in the lower image). The upper left image, which has an appearance similar to an x-ray, is a side view of the 3D image of the tube surface.

Materials Lab Featured Damage Mechanism

Pitting Corrosion in Conventional Fossil Boilers and Combined Cycle / HRSGs

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Pitting is a localized corrosion phenomenon in which a relatively small loss of metal can result in the catastrophic failure of a tube. Pitting can also be the precursor to other damage mechanisms, including corrosion fatigue and stress corrosion cracking. Pits often are small and may be filled with corrosion products or oxide, so that identification of the severity of pitting attack by visual examination can be difficult.

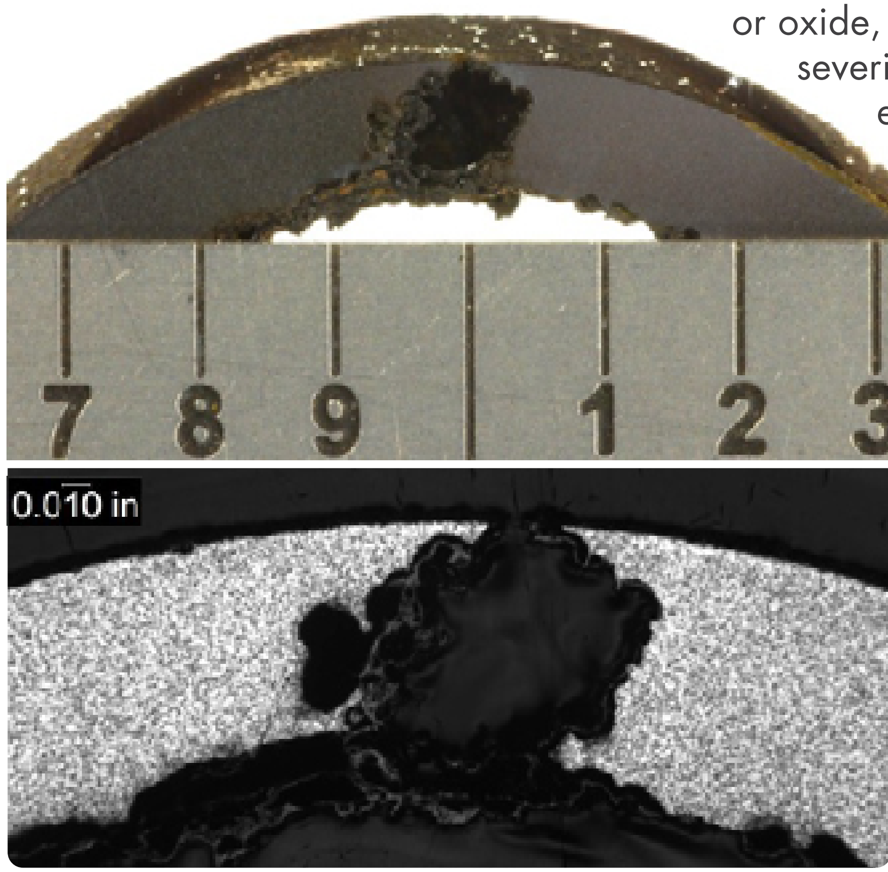

FIGURE 1. Severe pitting in a tube from a package boiler.

Mechanism

Pitting is a localized corrosion attack involving dissolution of the tube metal surface in a small and well-defined area. Pitting corrosion can occur in any component in contact with water under stagnant oxygenated conditions. Pitting in economizer tubing is typically the result of poor shutdown practices that allow contact with highly-oxygenated, stagnant water. Pitting also may occur in waterwall tubing as a result of acidic attack stemming from an unsatisfactory chemical cleaning or acidic contamination.

Pits that are associated with low pH conditions tend to be numerous and spaced fairly close together. The pits tend to be deep-walled compared to the length of the defect. A breakdown of the passive metal surface initiates the pitting process under stagnant oxygenated conditions. A large potential difference develops between the small area of the initiated active pit (anode) and the passive area around the pit (cathode). The pit will grow in the presence of a concentrated salt or acidic species. The metal ion salt (M+A-) combines with water and forms a metal hydroxide and a corresponding free acid (e.g., hydrochloric acid when chloride is present). Oxygen reduction at the cathode suppresses the corrosion around the edges of the pit, but inside the pit the rate of attack increases as the local environment within the pit becomes more acidic. In the event that the surfaces along the walls of the pit are not repassivated, the rate of pit growth will continue to increase since the reaction is no longer governed by the bulk fluid environment. Pitting is frequently encountered in stagnant conditions that allow the site initiation and concentration, allowing the attack to continue.

The most common cause of pitting in steam touched tubing results from oxygen rich stagnant condensate formed during shutdown. Forced cooling and / or improper draining and venting of assemblies may result in the presence of excess moisture. The interface between the liquid and air is the area of highest susceptibility. Pitting can also be accelerated if conditions allow deposition of salts such as sodium sulfate that combine with moisture during shutdown. Volatile carryover is a function of drum pressure, while mechanical carryover can increase when operating with a high drum level or holes in the drum separators. Pitting due to the effects of sodium sulfate may occur in the reheater sections of conventional and HRSG units because the sulfate is less soluble and deposits on the internal surfaces. During shutdowns the moisture that forms then is more acidic.

Typical Locations

In conventional units, pitting occurs in areas where condensate can form and remain as liquid during shutdown if the assemblies are not properly vented, drained, or flushed out with air or inert gas. These areas include horizontal economizer tubes and at the bottom of pendant bends or at low points in sagging horizontal tubes in steam touched tubes.

In HRSGs, damage occurs on surfaces of any component that is intentionally maintained wet during idle periods or is subject to either water retention due to incomplete draining or condensation during idle periods.

Attack from improper chemical cleaning activities is typically intensified at weld heat affected zones or where deposits may have survived the cleaning.

Features

Pits often are small in size and may be filled with corrosion products or oxide, so that identification of the severity of pitting attack by visual examination can be difficult.

Damage to affected surfaces tends to be deep relative to pit width, such that the aspect ratio is a distinguishing feature.

Root Causes

The primary factor that promotes pitting in boiler tubing is related to poor shutdown practices that allow the formation and persistence of stagnant, oxygenated water with no protective environment. Confirming the presence of stagnant water includes:

a. analysis of the corrosion products in and around the pit;
b. tube sampling in affected areas to determine the presence of localized corrosion; and
c. evaluation of shutdown procedures to verify that conditions promoting stagnant water exist.

Carryover of sodium sulfate and deposition in the reheater may result in the formation of acidic solutions during unprotected shutdown and can result in pitting attack. Similarly flyash may be pulled into reheater tubing under vacuum and form an acidic environment.

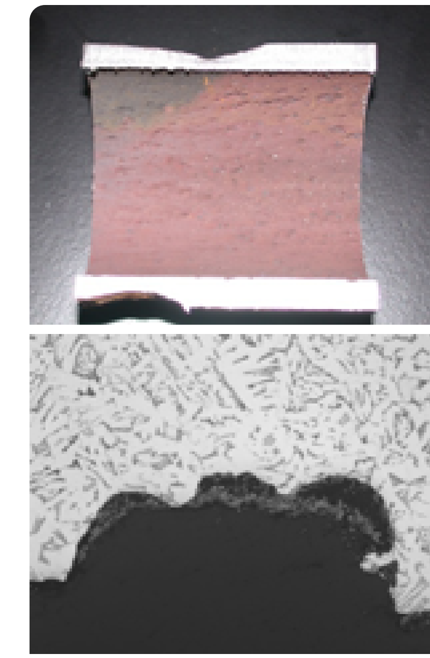
FIGURE 2. Pitting on the ID surface of a waterwall tube.

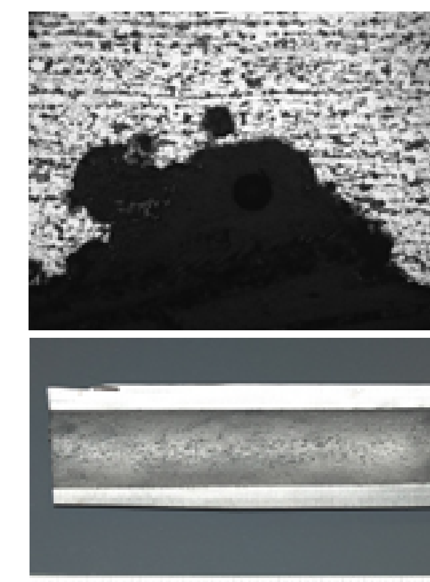
FIGURE 3. Pitting on the ID surface of an economizer tube.

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Pipeline Integrity

Activity and Plans for 2022

2021 marked another successful year for the Structural Integrity (SI) Oil & Gas team with several exciting pipeline integrity projects, industry presentations, training events and research programs. Some of the key highlights include:

- Continued regulatory consulting support of new pipeline safety regulation (known as Mega-Rule 1 or RIN 1) for nearly all our gas transmission pipeline clients.
- Commencement of a systemwide pipeline integrity project to evaluate the impact to pipeline safety and reliability from blending hydrogen with natural gas (at various blend levels) for one of the largest U.S. gas pipeline companies.
- Several industry presentations and training seminars on fracture mechanics evaluation of crack and crack-like defects in support of Predicted Failure Pressure (PFP) Analysis and Engineering Critical Assessments (ECA).
- Completion of a PRCI study on state-of-the-art technology and a technology benchmark evaluation of X-Ray Computed Tomography to characterize Stress Corrosion Cracking (SCC) on full circumferential samples.
- Development of a Neural Network algorithm and application of Probabilistic Fracture Mechanics to provide insight on the risk of SCC for a large interstate natural gas pipeline operator.
- Development of an alternative sampling program for Material Verification when using In-Line Inspection tools including development of regulatory submittals.

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2022 is also shaping up to be a similarly busy and exciting year. Below are some of the events, conferences and presentations SI has currently planned or recently attended:

- **At the PRCI Research Exchange on March 8th in Orlando, FL, SI presented on two recent projects: Insights in the Evaluation of Selective Seam Weld Corrosion**
  This paper reviewed a statistical analysis of ERW Fracture Toughness and specific challenges in evaluating Selective Seam Weld Corrosion (SSWC). It also reviews the results of an engineering critical assessment performed on a pipeline system in which several SSWC defects were identified. Fracture Toughness Testing and Finite Element Modeling were performed to develop insights that were used to support Predicted Failure Pressure analysis and subsequent prioritization and remediation activities.
  Title: Evaluation of X-Ray Computed Tomography (XRCT) for Pipeline Reference Sample Characterization
  This presentation reviewed the feasibility of utilizing XRCT for nondestructively characterizing full-circumference pipeline reference samples for subsequent qualification and performance improvement of inline inspection and in-the-ditch nondestructive evaluation technologies, procedures, and personnel. This presentation will cover the state-of-the-art in XRCT, reviewing theoretical and practical concepts, as well as empirical performance data, that were evaluated and analyzed to determine the feasibility of using XRCT for this application.

- **SI has two papers that will be presented at the American Gas Association – Operations Conference the week of May 2nd in New Orleans, LA: Alternative MV Sampling Program**
  SI will present technical justification in support of PHMSA notification with regards to the following:
  - Alternative sampling for Material Verification Program (per §192.607).
  - Expanded MV Sampling Program that will achieve a minimum 95% confidence level when material inconsistencies are identified.

  A Framework for Evaluating Hydrogen Blending in Natural Gas Transmission Pipelines
  Operators are establishing programs to blend hydrogen with natural gas. Structural Integrity (SI) is supporting a local distribution company to ensure safe and reliable blending and transportation in existing pipeline infrastructure. SI will present a reliability framework to identify pipelines that are best suited at different H2 blend levels.

- **SI will present at the 2022 ASME - International Pipeline Conference on the following topic: Probabilistic Analysis Applied to the Risk of SCC Failure**
  This paper will discuss a model developed and applied to evaluate the probability of Stress Corrosion Cracking (SCC) failure in a large gas pipeline system spanning approximately 5,600 miles. A machine learning algorithm (neural network) was applied to the system, which has experienced over 500 prior instances of SCC. Subject matter experts were interviewed to help identify key system factors that contributed to the prevalence of SCC and these factors were incorporated in the neural network algorithm. Key factors such as coating type, vintage, operating stress as a percentage of SMYS, distance to compressor station, and seam type were evaluated in the model for correlation with SCC occurrence. A Bayesian analysis was applied to ensure the model aligned with the prevalence of SCC. A Probabilistic Fracture Mechanics (PFM) model was then applied to relate the probability of SCC existing to the probability of rupture.

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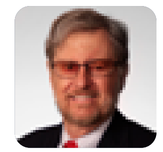
Selective Seam Weld Corrosion

Engineering Critical Assessment



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The Structural Integrity Associates, Inc. Oil and Gas Pipeline group recently supported an Engineering Critical Assessment to assist a pipeline operator manage the Selective Seam Weld Corrosion (SSWC) threat to an operating pipeline. SSWC occurs when the fusion zone of a certain type of seam weld used in vintage (pre-1970) transmission pipelines experiences accelerated galvanic corrosion relative to the pipe body material. It has led to numerous pipeline failures because the weld fusion zone often exhibits low fracture toughness. The ECA included several technical advancements in applying fracture mechanics to this threat.

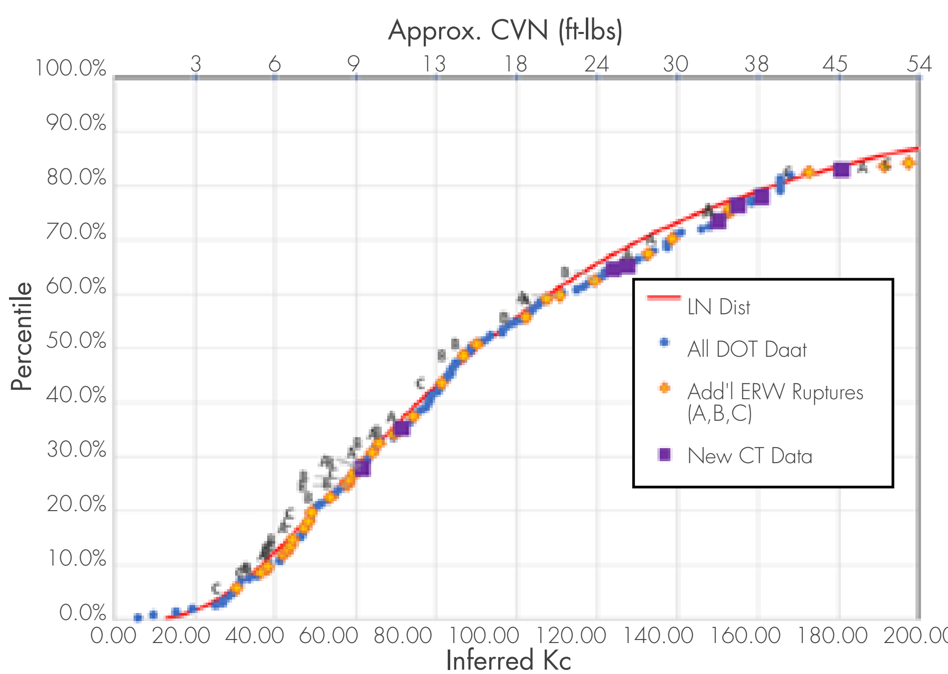

FIGURE 1. Cumulative Distribution of Fracture Toughness from Historical Failures of ERW/FW Seam Welds with New Fracture Toughness Measurements Added (Purple Squares)

The technical advancements included:

- Estimating fracture toughness from test samples extracted from the pipeline, superposed on SI's historical database of vintage Electric Resistance Weld (ERW) and Flash Weld (FW) toughness based on prior failures (see Figure 1),
- Evaluation of Compact Tension JR-Curve and Charpy V-notch Test Results on representative samples,
- Analyzing metallurgical photo-micrographs of several SSWC-like defects removed from the pipe (see Figure 2),
- Incorporating constraint adjustments for thin-wall pipe to convert plane strain toughness (KIc) into toughness that better represents the fracture resistance of thin-walled pipe (Kc),
- Critical flaw size calculations using the API-579 Level II Fracture Mechanics methodology,
- Finite element modeling of various SSWC defect geometries to evaluate the impact of Grooving Factor on reduction in crack tip stress intensity (see Figure 3),
- Supporting client in sample selection and testing for future steps that include burst testing and In-Line Inspection.

Fracture toughness measurements on ERW fusion line samples from pipeline digs were added to a prior fracture toughness distribution developed by SI from approximately ~175 ERW / FW pipeline ruptures to develop a 10th percentile recommended toughness of 36.5 ksi√in (≈5 ft-lbs) for SSWC anomalies in this pipeline. Fracture Mechanics analyses using this recommended toughness yielded critical crack depths at MAOP (650psi) greater than 60% of wall thickness for relatively long, crack-like features (Length greater than 6 inches). Critical crack depth calculated for a 1991 hydrotest of the line (at 1164 psi) were greater than 40% of wall thickness. The analysis correctly predicted the hydrotest result (non-failure), thus corroborating the recommended fracture toughness and establishing a Safety Factor of 1.8 at the time of the test, with margin for flaw growth.

To further corroborate the fracture toughness, a burst test of the worst case SSWC-like feature extracted from a series of additional digs is planned. An ILI Pull Test was also performed on a set of dig samples to demonstrate the effectiveness of various ILI tools that will be used to assess the potential for flaw growth since the 1991 hydrotest.

More detail on this work was recently published at the Pipeline Research Council International (PRCI) 2022 Research Exchange.

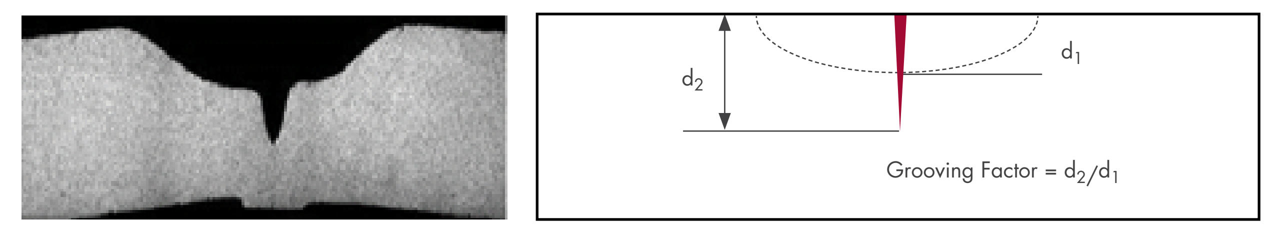

FIGURE 2. Illustration of ERW/FW Sean Weld with SSWC and Associated Grooving Factor Definition

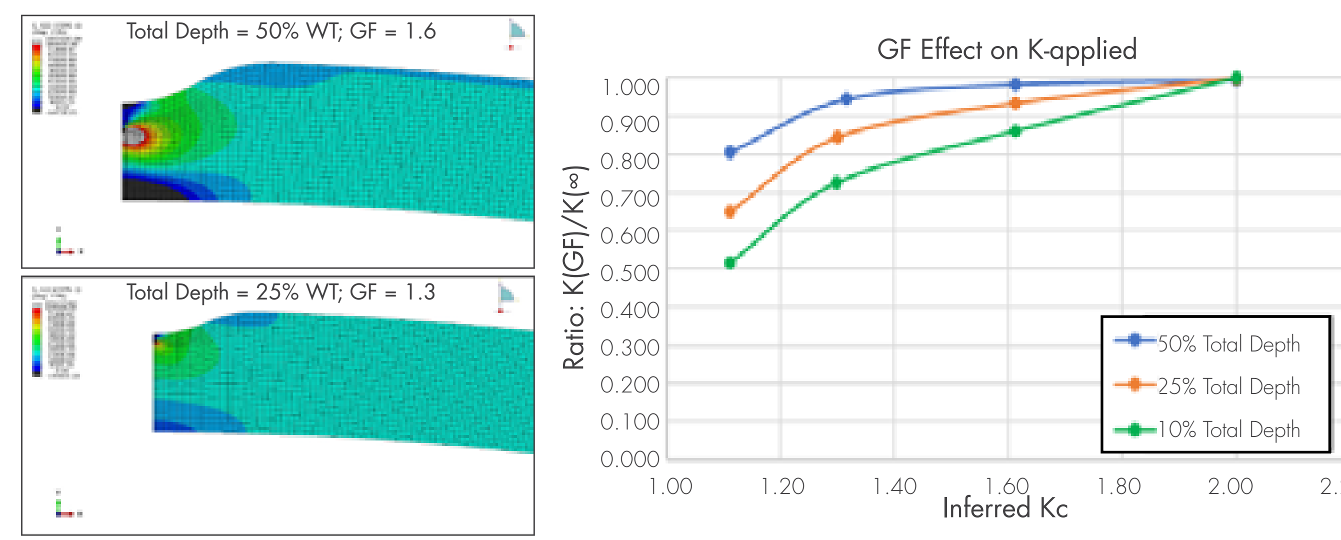

FIGURE 3. Finite Element Model and Results of a Study to Evaluate the Effect of SSWC Grooving Factor on Applied Stress Intensity Factor

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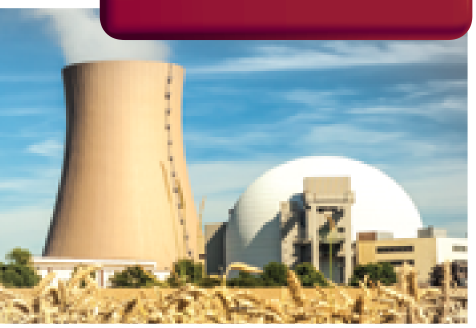
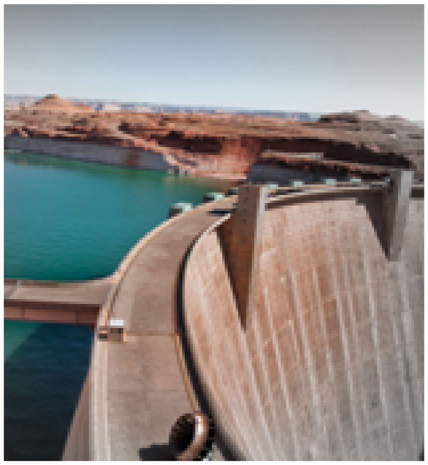
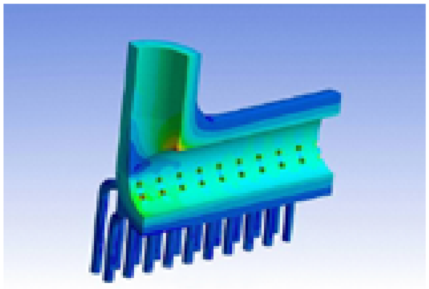
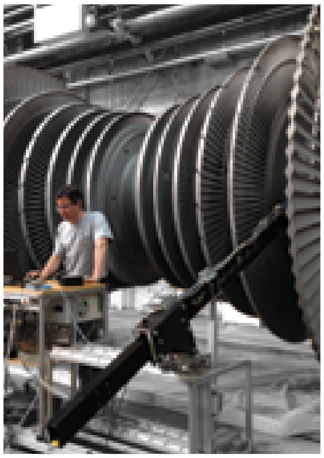
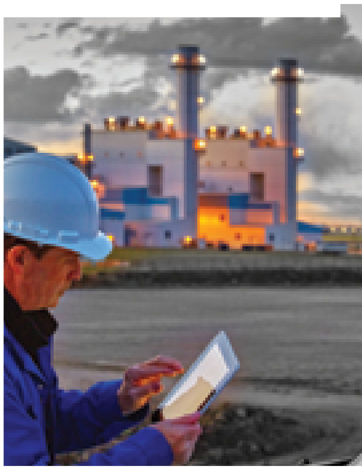
ASSET INTEGRITY & LIFE CYCLE MANAGEMENT











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SI has expertise ranging from engineering analysis to R&D, metallurgy, and non-destructive testing across all facets of the energy industry and has a rich history preventing and managing structural & mechanical failures. SI experts are recognized leaders for developing innovative solutions – strategies that are less invasive and more effective, efficient, and affordable. Nearly every utility in the United States has relied on SI to support a safe and reliable operation.

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