2022 | VOLUME 52

Structural Integrity Associates, Inc.®

NEWS & VIEWS

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Online Monitoring of HRSG with SIIQ™ pg. 28

A CASE STUDY ON IMPLEMENTATION AT A 3x1 COMBINED CYCLE FACILITY (ARTICLE 1 OF 3)

CEO Message

MARK W. MARANO
President and CEO
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It has been a very rewarding year for Structural Integrity Associates (SI), and I believe, good for our client base as well. As President and CEO of the company, I want to take this opportunity to touch upon a few things about our business. SI is growing. Our top-line revenue is growing 10% year over year, and our newfound operating efficiencies will lead us to one of our most (perhaps the most) profitable years. SI is now in an excellent position to continue making advancements in our technology offerings, continued investment in R&D, and additional capital investments like the 2022 acquisition of the turbine-generator inspection business from Sonomatic, Inc., which has added capabilities to our turbine services.

Evident in this issue of News & Views are the results of technology investments SI has made. Take a look at the first of a three-part series on SIIQ™ – our intelligent monitoring and predictive suite of services, continued updates to our independently developed PEGASUS™ fuel code software, innovations in predicting the life of concrete, hydrogen and gas in-pipeline blending, and more. I am proud of the work SI is doing to continue advancing itself as a premium engineering consulting firm and our offering of outstanding NDE technology.

Our continued commitment to growth, technological advancement, and client service is visible in our 2022 'hiring blitz,' where we hired an additional 20% of employees during one of the most challenging labor markets ever seen. We successfully added additional positions across all business areas, including technical positions across our Nuclear, Energy Services Group, Oil & Gas, and Critical Structures. Remarkably, our retention is also extremely high despite the hiring climate.

Our financial performance allows us to invest even more in our businesses. I am proud and greatly appreciate our clients' support in trusting us for complex, emergent, and ongoing work in some of our critical areas. Over the last three years, we have focused on aligning our business and staff that support our business model, including the management team, engineering support services, and our NDE technicians. All of our businesses are moving in the right direction, and I am optimistic that SI will continue to prosper on the platform we have staged.

As you may have seen, on December 1st, SI announced its partnership with Jumana Capital (Jumana) and C2C Technical Services (C2C). SI's shareholders and employees showed their support for the change with a 98% shareholder approval vote. Jumana is a family fund with one primary investor and differs greatly from a typical Private Equity firm. Instead of the typical synergistic play to facilitate corporate cost-cutting, this partnership will allow SI to offer support to C2C as they continue to grow their business. I am very pleased with this partnership as it ensures we can continue operating SI in a similar fashion.

Whereas SI focuses on engineering and NDE, C2C complements our services with a focus on in-field work and design engineering. This partnership will offer our collective client base a larger suite of services. This is an exciting opportunity for SI to grow further by making additional investments in our pursuit of both organic and inorganic growth.

As we move forward, I will maintain the President and CEO role at SI while adding the responsibilities of President / CEO for SI Solutions. SI Solutions is the holding company created for SI, C2C, and future acquisitions. This platform will allow our businesses to support the core requirements needed in our country's infrastructure, including energy generation and distribution, oil and gas, and critical structures.

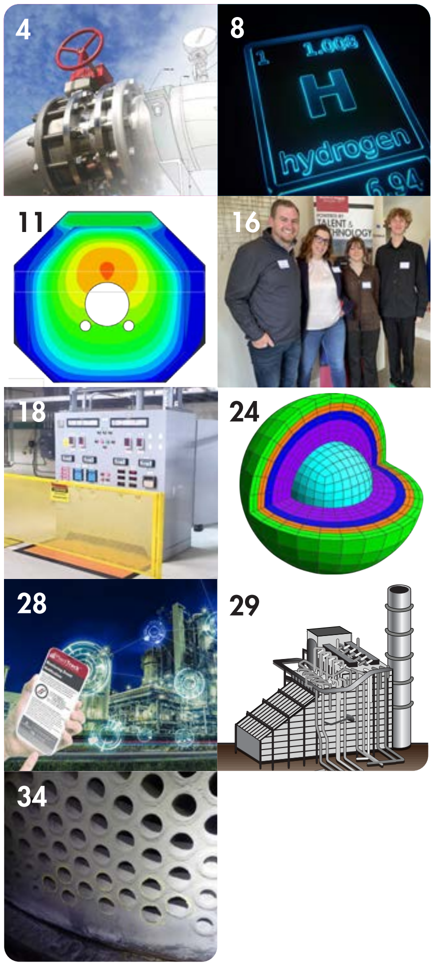
It will be a very exciting time, and I look forward to leading this organization. Although there is not yet a projected timeline, I will eventually migrate the SI CEO role to an apparent successor.

I look forward to an exciting year where the future looks bright for SI with continued support from you, our valued clients. Enjoy News & Views Volume 52 and the exemplary technological advancements discussed within.

We look forward to the new year ahead,

Mark

In this Issue



PHMSA Rupture Mitigation Valve Rule

Preparing Clients to Meet New Pipeline and Safety Regulation

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On April 8, 2022, the Pipeline and Hazardous Materials Safety Administration (PHMSA) published amendments to 49 CFR Part 192 in the Federal Register issuing new valve installation and rupture detection requirements for onshore transmission pipelines and gathering pipelines . The effective date of the Final Rule ("Valve Rule") is October 5, 2022.

GENERAL OVERVIEW

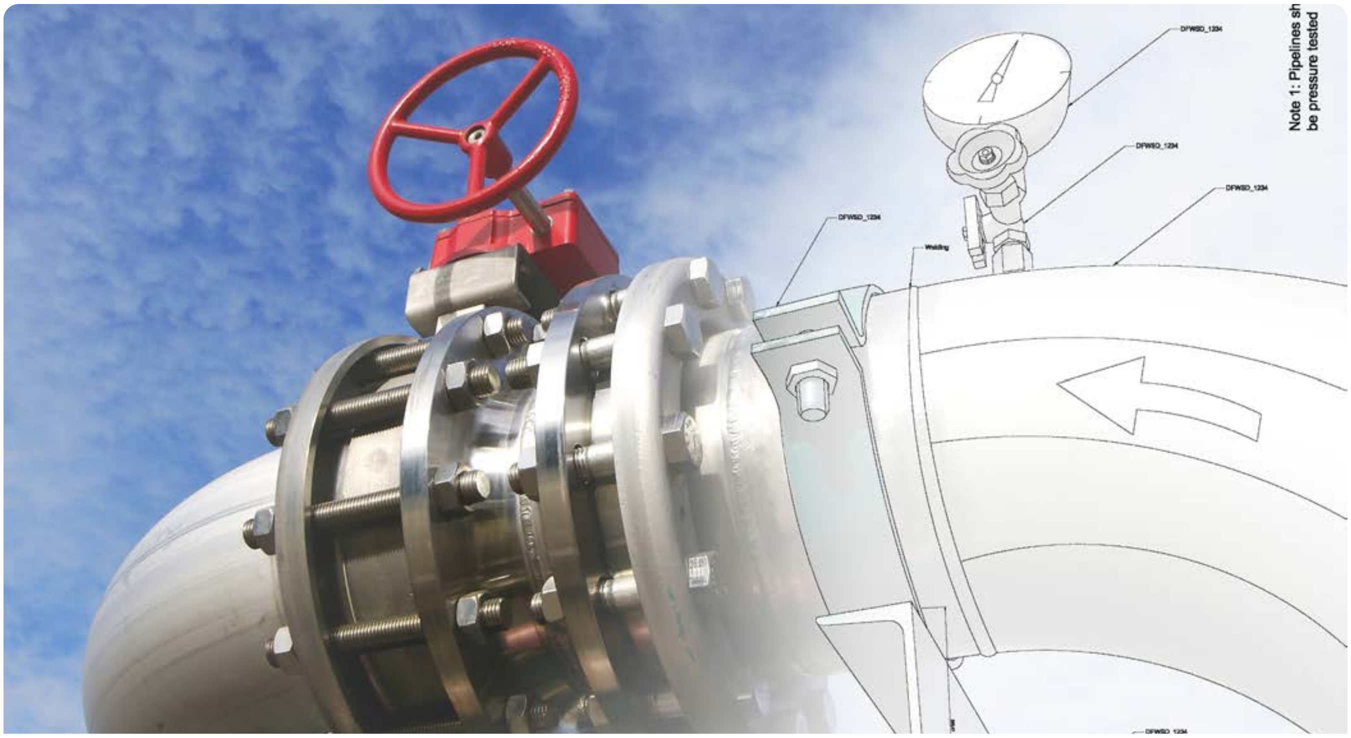
As a result of two high-profile transmission pipeline accidents in 2010 , the congressional Pipeline Safety, Regulatory Certainty, and Job Creation Act of 2011 (2011 PIPES Act) was enacted. The legislation contained several mandates for PHMSA to issue regulations addressing improvements to pipeline safety. One of the mandates required PHMSA to issue regulations for the use of Automatic Shut-off Valves (ASV) or Remote-Control Valves (RCVs), or equivalent technology, on newly constructed or replaced gas transmission pipeline facilities.

The Valve Rule addresses this congressional mandate by establishing minimum standards for the installation of Rupture Mitigation Valves (RMVs) or alternative equivalent technology (AET) on specified newly constructed or entirely replaced onshore natural gas transmission, Type A gas gathering and hazardous liquid (e.g., oil and gasoline) pipelines that have diameters of 6 inches or greater.

> The new rule is complex and creates challenges for operators. Since 2011, Structural Integrity has been advancing practical and cost-efficient methods to address pipeline safety.

The Valve Rule covers the following topics:

- New Definitions
- Rupture Mitigation Valves (RMVs)
- Changes in Class Location and Valve Spacing
- Emergency Plans and Response
- Failure and Incident Investigation
- Notification of Potential Rupture and Response to Rupture Identification
- Valve Shutoff Requirements for Rupture Mitigation
- RMV Valve Maintenance
- Preventative and Mitigative Measures for Pipelines in HCAs



NEW DEFINITIONS (§192.3)

The Valve Rule defined “notification of potential rupture” as notification of, or observation by an operator, of the specific indications of an unintentional or uncontrolled release of a large volume of natural gas from a pipeline. PHMSA has defined “rupture identification” to mean the point when a pipeline operator has sufficient information to reasonably determine that a rupture occurred.

RUPTURE MITIGATION VALVES (RMVs) (§192.179)

The Valve Rule prescribes new rupture mitigation valve (RMV) installation requirements on certain pipeline segments with diameters of six inches or greater that are constructed or “entirely replaced” after April 10, 2023 in accordance with §192.179. The RMV installation requirements only apply to entirely replaced pipelines if the addition, replacement, or removal of a valve is part of the replacement project.

> "Entirely replaced" is defined as replacing two or more miles, collectively, of any contiguous five miles of pipeline during a 24-month period.

Gas pipeline segments in Class 1 or Class 2 locations that have a potential impact radius (PIR) of 150 feet or less are exempt from RMV installation requirements.

An RMV is defined as an automatic shut-off valve (ASV) or remote-control valve (RCV) “that a pipeline operator uses to minimize the volume of gas released from the pipeline and to mitigate the consequences of a rupture.”

Operators may elect to use an alternative equivalent technology (AET) in response to the RMV installation requirements if the AET provides an equivalent level of safety. This process must be demonstrated and requested by the operator in a notification pursuant to §192.18 for PHMSA review. An operator requesting use of manual valves as an AET must include in the notification submitted to PHMSA a demonstration (e.g., evidence) that installation of an RMV would be economically, technically, or operationally infeasible.

CHANGES IN CLASS LOCATION AND VALVE SPACING (§192.610)

The Valve Rule also applies where class location changes occur, and gas pipeline replacements are necessary to comply with Part 192 maximum allowable operating pressure (MAOP) requirements. For Class Location changes that occur after October 5, 2022, and which are considered being entirely replaced, operators are required to comply with the valve spacing and RMV installation requirements. These valves must be installed within 24 months of the change in Class Location.

Continued on next page

For replacements not considered entirely replaced, the operators must either:

(1) Comply with the valve spacing requirements in accordance with §192.179(a) for the replaced segment, or

(2) Install or use RMVs or AETs so that the entirety of the replaced pipeline segment is between two RMVs or AETs. The distance between the RMVs/ AETs may not exceed 20 miles.

The requirements above do not apply to pipeline replacements that are less than 1,000 feet within any single continuous mile during any 24-month period.

EMERGENCY RESPONSE (§192.615(A))

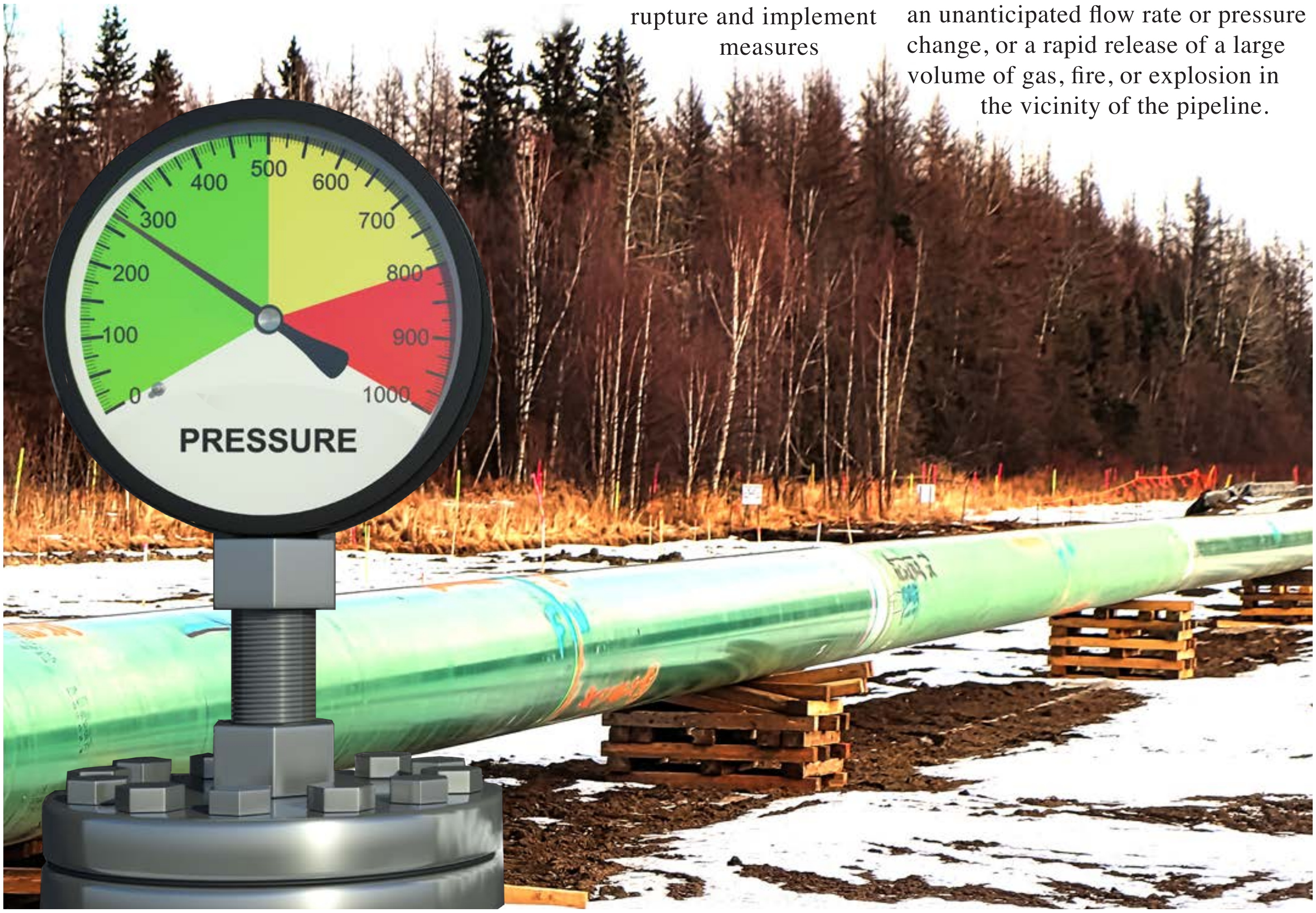
In the event of a potential or confirmed transmission or distribution pipeline rupture, the Valve Rule prescribes new requirements for operators to establish and maintain communication with appropriate public safety answering points (i.e., 9-1-1 emergency call center). Operators must revise their procedures to require immediate and direct communication to 9-1-1 call centers or coordination with local government officials located in the communities and jurisdictions in which the pipeline rupture is located.

FAILURE AND INCIDENT INVESTIGATION (§192.617)

In the event of a pipeline rupture involving the closure of an RMV and/or AET, an operator must conduct an analysis of the factors that may have contributed to the rupture and implement measures to minimize the consequences of a future incident. Operators must also complete a summary of the post-failure or incident review within 90 days of the incident. The summary must be signed by a senior executive officer and retained for the useful life of the pipeline.

NOTIFICATION OF POTENTIAL RUPTURE AND RESPONSE TO RUPTURE IDENTIFICATION (§192.635)

The Valve Rule requires operators who identify a potential rupture or are notified directly from an external credible source(s) of a potential rupture, to take action(s) on their transmission pipeline system. "Notification of potential rupture" may be based on one or more indications such as an unanticipated pressure loss greater than 10 percent in 15 minutes or less, an unanticipated flow rate or pressure change, or a rapid release of a large volume of gas, fire, or explosion in the vicinity of the pipeline.



An operator must develop procedures documenting how it observes a potential rupture or receives notification of a potential rupture and the actions to be taken in response to a potential and confirmed rupture. Upon notification of a potential rupture, operators must evaluate the potential rupture as soon as possible to confirm if it is a rupture.

VALVE SHUTOFF REQUIREMENTS FOR RUPTURE MITIGATION (§192.636)

The Valve Rule prescribes new valve shut-off requirements. After rupture confirmation, the operator must fully close any appropriate RMVs or AETs necessary to minimize the volume of gas released from a pipeline and mitigate the consequences of the rupture as soon as practicable but within 30 minutes of rupture identification. Other valves necessary to isolate the pipeline segment must be closed as soon as practicable.

VALVE MAINTENANCE (§192.745)

PHMSA revised the existing §192.745 to require operators to conduct valve maintenance, inspection, and operator drill activities to ensure each RMV or AET can achieve the prescribed 30-minute valve closure time. If during the drill, the 30-minute response time is not achieved, the operator must revise its rupture response efforts as soon as practicable to achieve compliance, but no later than 12-months after the drill. Any valve found inoperable during this test must be repaired or replaced as soon as practicable but no later than 12 months after the valve is determined to be inoperable. The operator must also select an alternative valve to act as an RMV within seven calendar days.

PREVENTATIVE AND MITIGATIVE MEASURES (§192.935)

The Valve Rule requires gas transmission operators to conduct a risk analysis/assessment on their transmission pipeline system to analyze whether an RMV or AET is an efficient means of adding protection to an HCA. The risk analysis/assessment must consider timing of leak detection and pipe shutdown capabilities, the type of gas being transported, operating pressure, the rate of potential release, pipeline profile, the potential for ignition, and the location of the nearest response personnel. The risk analysis/assessment must be reviewed by operator personnel at least once per calendar year, not to exceed 15 months, and certified by a senior executive.

SI PROVIDES OPERATOR SUPPORT

Structural Integrity has significant expertise in pipeline safety regulatory compliance and has been heavily involved in the Valve Rule since 2011. Our dedicated and substantial resources are ready to help with specific procedures and programs, including:

- Risk Analysis and Assessment of RMVs on transmission pipeline systems.
- Review and update of all existing procedures impacted by the new regulatory requirements, including emergency response, valve installation, operations, and maintenance.
- Development of new, comprehensive procedures and processes to support compliance with the Valve Rule, which include defining Gas Control Room responses to potential ruptures, significant gas releases, and confirmed ruptures.

Reference

(1) PHMSA Pipeline Safety: Requirements of Valve Installation and Minimum Rupture Detection Standards Final Rule.

Understanding the Effects of Hydrogen Blending on Pipeline Integrity

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Structural Integrity Associates is focused on evaluating the impact of hydrogen blending on pipeline integrity and establishing a roadmap for our clients to maintain the safety and integrity of their aging natural gas steel transmission pipelines.

Hydrogen is widely recognized as a viable, clean alternative energy carrier. Recent advances in technology for clean hydrogen production, as well as renewed governmental and organizational commitments to clean energy, have intensified interest in utilizing the existing natural gas pipeline infrastructure to transport hydrogen from production sites to end users. Energy companies are pursuing strategic pilot programs to evaluate the capacity of their natural gas transmission and distribution pipeline systems to safely transport blends of natural gas and hydrogen. These pilot programs demonstrate the commitment of energy companies to facilitate environmentally responsible energy production and consumption while identifying and investigating potential challenges to pipeline safety and integrity associated with hydrogen blending.

KEY ELEMENTS OF THE EVALUATION INCLUDE

- Completing a critical threat review using a phenomena identification and ranking table (PIRT) process with a team of experts.
- Developing a statistical model for evaluating accelerated fatigue crack growth (FCG) in a hydrogen blend environment.
- Developing a statistical model for evaluating reduced fracture resistance (hydrogen embrittlement).
- Analyzing the impact of FCG and hydrogen embrittlement on the probability of rupture (POR) due to key threats such as stress corrosion cracking (SCC), longitudinal seam weld defects, and hard spots.
- Implementing a joint industry project (JIP) to adapt SI's APTITUDE software tool for evaluating predicted failure pressure (PFP) and remaining life resulting from SCC and FCG in a hydrogen blend environment.

CRITICAL THREAT REVIEW

As part of a systemwide evaluation for one of our clients, a large North American Pipeline Operator, a critical threat review using a PIRT process was conducted to comprehensively understand the potential impact of hydrogen blending on steel natural gas transmission pipeline integrity. To ensure a thorough and accurate PIRT was completed, a panel consisting of experts in metallurgy, fracture mechanics, hydrogen effects on steel properties, and pipeline operations was assembled. A vital part of the process was a series of meetings conducted with the pipeline operator, systematically identifying and ranking the importance of various phenomena that could adversely affect the safety and reliability of energy transportation through the operator's existing transmission pipeline system.

The PIRT panel reviewed all known pipeline integrity threats and identified potential unknown or unexpected threats that could be influenced by the presence of hydrogen in the operator's transmission pipeline system. The process also assigned priorities for future research that may be needed to support that objective.

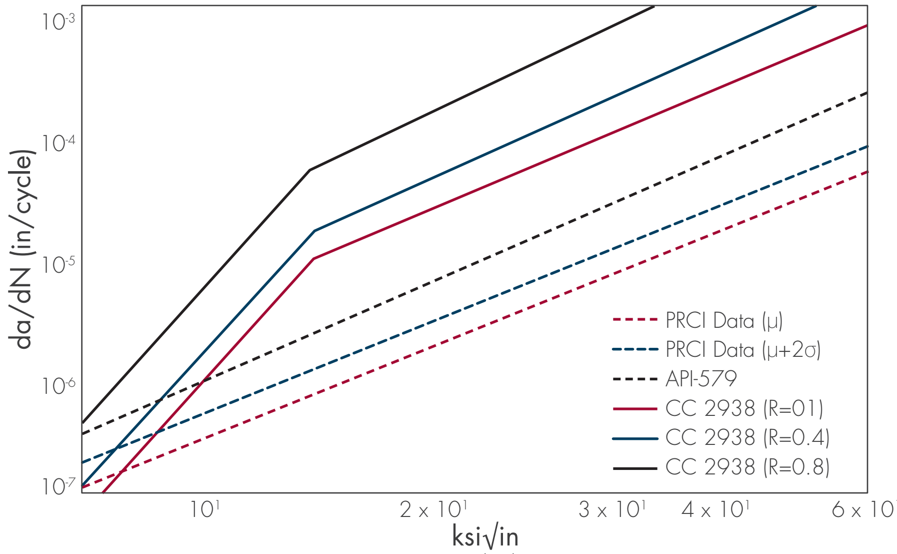

FIGURE 1. FCG rate curves in hydrogen (SOLID LINES) versus air (DASHED LINES).

ENHANCED FATIGUE CRACK GROWTH

Significant research exists on the effect of hydrogen on FCG of pipeline steels and was referenced in this exercise. To gather the most relevant information possible, the project team compiled and analyzed data from numerous client-specific FCG tests of samples taken from the pipeline system in the targeted environment. These sample systems were exposed to equivalent hydrogen blend levels of 5%, 10%, 20%, and 100%. Over 2,200 data points were compiled and analyzed to develop trend curves and associated statistical variability. Data exhibited a significant increase in FCG rates (Figure 1) at relatively low hydrogen blend levels. ASME Code Case 2938 was reviewed and empirically fit with the analyzed data.

HYDROGEN EMBRITTLEMENT

Hydrogen is known to have an embrittling effect on carbon steels, such as those used in gas transmission pipelines. When an internal pipe surface is exposed to high-pressure hydrogen or a high-pressure mixture of hydrogen and natural gas, hydrogen gas can disassociate into hydrogen atoms, which can then be adsorbed into the steel and lead to material property degradation (such as reduced fracture resistance). Dislocations and defects in the steel can also act as hydrogen traps, leading to even higher hydrogen concentrations at the location of already vulnerable manufacturing defects and service-induced cracks. Reduced fracture resistance at such sites could

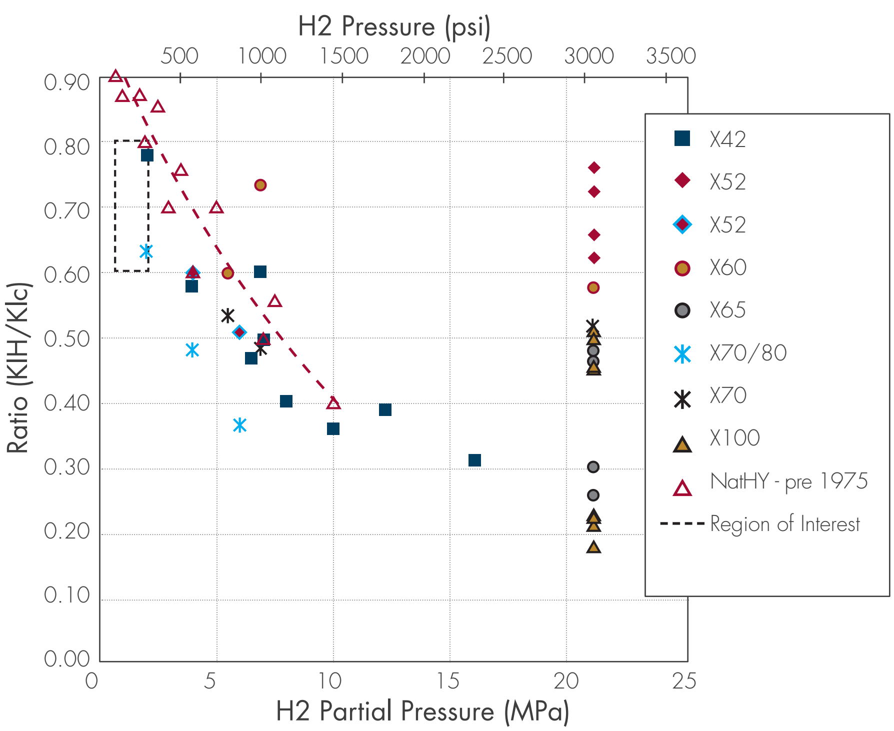

FIGURE 2. Fracture toughness reduction as a function of hydrogen partial pressure for different pipe grades.

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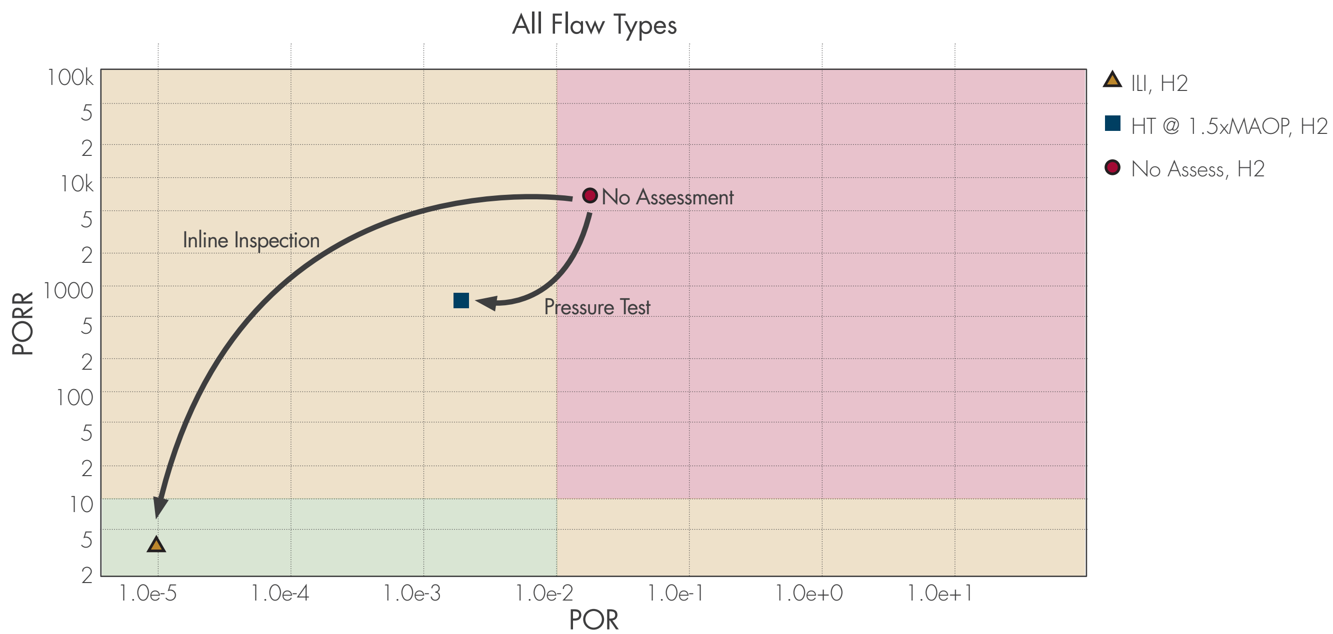

FIGURE 3. Improvement in POR and PORR for different integrity assessments.

increase the adverse effect on pipeline integrity by leading to more frequent pipe failure events.

Based on available data from the literature and input from the PIRT expert panel, the project team developed trend curves of percent reductions in fracture resistance due to hydrogen exposure (knockdown factors) relative to fracture toughness in air. From this analysis, a reasonably conservative approximation, including statistical variability, was developed for the region of interest (hydrogen/natural gas blend levels up to 20% - Figure 2). Additional research and data analysis are currently underway that may further validate the relationship and better study this effect at low hydrogen partial pressures, as well as confirm the knockdown effect on lower toughness pipeline materials, such as electric resistance welded (ERW) seam welds.

PROBABILISTIC FRACTURE MECHANICS

SI has developed Synthesis™ , a Probabilistic Fracture Mechanics (PFM) tool that calculates the probability of rupture (POR) for various cracks and crack-like defects that have caused oil and gas pipeline failures. The software incorporates statistical distributions of all important parameters in a pipeline fracture mechanics calculation that uses a Monte Carlo analysis algorithm that randomly samples from each distribution and runs millions of simulations to estimate the probability of rupture versus time. To evaluate the impact of hydrogen blending, Synthesis has been adapted to incorporate the effects of hydrogen on pipeline steel properties (enhanced FCG and hydrogen embrittlement) and thus the ability to compare PORs with and without hydrogen blending. The modified software was then applied to several pipelines in the operator's system to determine the POR ratio between various hydrogen blend levels and pure natural gas. Additionally, Synthesis can evaluate the effects of various mitigation measures, such as hydrotests and In-Line Inspections, that could be applied before injecting hydrogen (Figure 3). The calculated PORRs will allow the operator to prioritize pipelines and associated mitigating actions that may be more or less favorable for hydrogen blending.

APTITUDE™ JOINT INDUSTRY PROJECT

SI has also established a JIP to adapt the APTITUDE PFP software program to handle some additional challenges presented with blending hydrogen with natural gas. Advancements include modifications that address enhanced FCG and hydrogen embrittlement. Further research to close gaps identified during the PIRT process is also being pursued through PRCI and other forums. Availability to join the JIP still exists, but space is limited - Please contact us if you would like to participate.

Forecasting the Life of a Mass Concrete Structure, Part Two

A Case Study from the Fermilab Long Baseline Neutrino Facility

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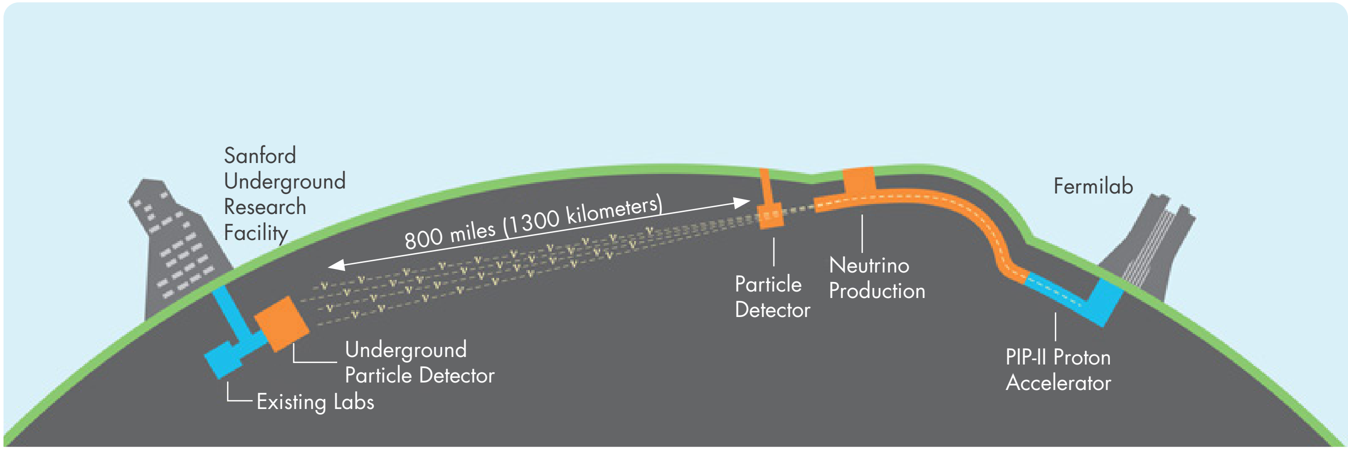

FIGURE 1. Fermilab Long Baseline Neutrino Facility (source https://mod.fnal.gov/mod/stillphotos/2019/0000/19-0078-02.jpg)

REFRESHER OF PART 1

From part one of the article (see News and Views Volume 51), we looked at the performance of a unique tubular mass concrete structure – the decay region of Fermilab's Long Baseline Neutrino Facility – under complex thermal loading and thermal expansion. In the process of colliding subatomic particles in an accelerator and beaming them across the country underground, the facility contends with a massive amount of heat, an active nitrogen cooling system to remove energy, and shielding necessary for the surrounding environment. As we discussed in Part 1, Structural Integrity assisted with the design of the concrete structure by calculating the pertinent structural and thermal behavior under normal operation. Now for Part 2, we focus on forecasting the future life of the structure using advanced capabilities in analysis and delve into the actual life of this concrete structure while considering the construction process, a 30 year planned cycle of life, and how these influence planning for structural monitoring systems. In doing so, we attempt to answer a larger question: What can we learn from this structure that could be applied to other past and future structures?

These methods are not only applicable to new structures. Armed with the knowledge we can gain from record drawings, visual inspection, and non-destructive examination, SI is able to predict the life of concrete structures, new and old, giving key insights into their behavior in the future.

HEAT OF HYDRATION

In understanding the life of a structure, we must first start at the beginning as the concrete is first poured where another heat transfer takes place. Contrary to popular belief, concrete does not “dry”, rather it “bakes” itself during the curing process. As concrete is poured, it begins heating up internally through an exothermic hydration reaction between water and cement. The effect of the heat of hydration can usually be ignored in typical thin-walled structures. In larger mass concrete structures, however, the heat generation can cause significant degradation and built-in damage that can affect the structural performance throughout the entire life of the facility.

A secondary subroutine as part of the ANACAP models is used for heat of hydration specific for construction analysis to convert the temperature rise into volumetric heat generation rate for thermal analysis. When heat is trapped deep inside the structure and can’t escape, the concrete exhibits a temperature rise similar to the curve in Figure 2, which is a function of the concrete mix proportions.

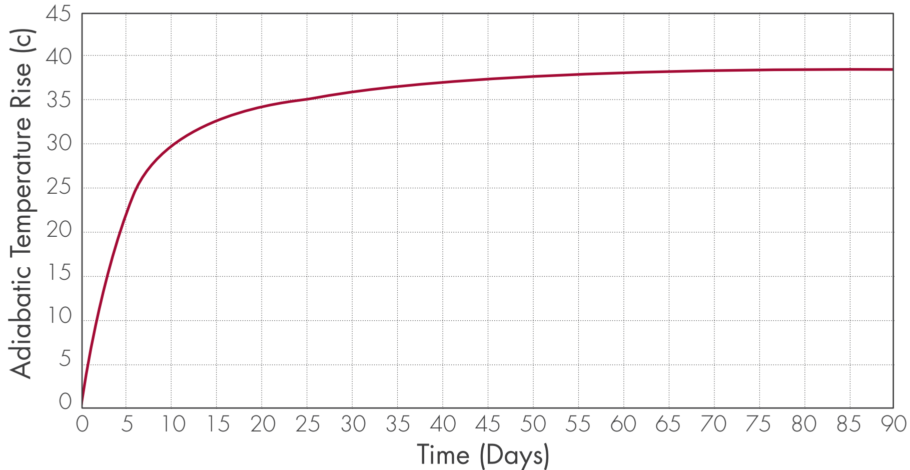

FIGURE 2. Adiabatic Temperature Rise for Concrete Placement

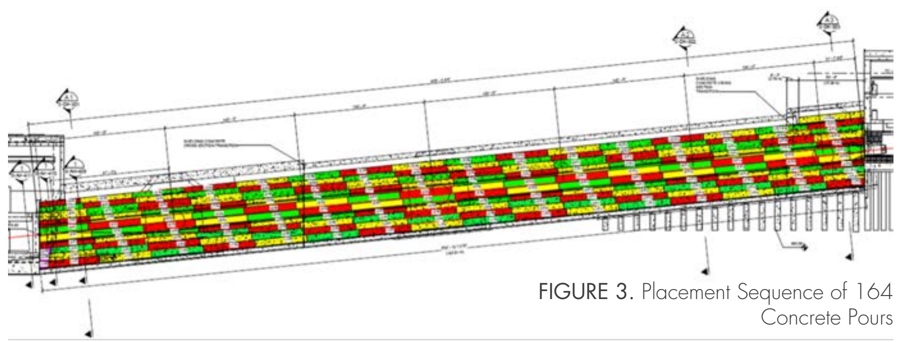

FIGURE 3. Placement Sequence of 164 Concrete Pours

CONSTRUCTION ASSESSMENTS

For the operating conditions covered in Part 1, the coupled 3D thermal stress analyses performed on this project were thermal conduction steady-state analyses. Construction of such a large concrete structure is subjected to additional requirements, and a Nonlinear Incremental Structural Analysis (NISA) was performed to evaluate the structure under the construction loadings. Herein, the thermal analysis during the concrete placement sequence requires a transient numerical solution methodology. This thermal analysis was used to monitor additional requirements for temperature during concrete placement, and a mechanical NISA study monitored the movement of the central cooling annulus vessel. The complete NISA coupled thermal-stress analysis simulated the entire construction phase over the period of a year and a half of the planned construction schedule. To accomplish this, the model was segmented into 164 concrete pours, each one activated (turned on) within the model on a specific day outlined in a construction schedule, as shown in Figure 3. As the concrete is poured on its specific day, the heat of hydration begins to heat up the internals of the concrete, the outside ambient temperature pulls the heat away from the concrete, and formwork insulates the heat transfer temporarily before being removed. As each new concrete segment is poured (activated in the simulation) it begins a new heat cycle, shedding heat into surrounding segments, changing surfaces that are exposed to air, or where the formwork is located. Upon completion of the thermal NISA study, Structural Integrity could advise on peak temperatures of each pour (Figure 4),

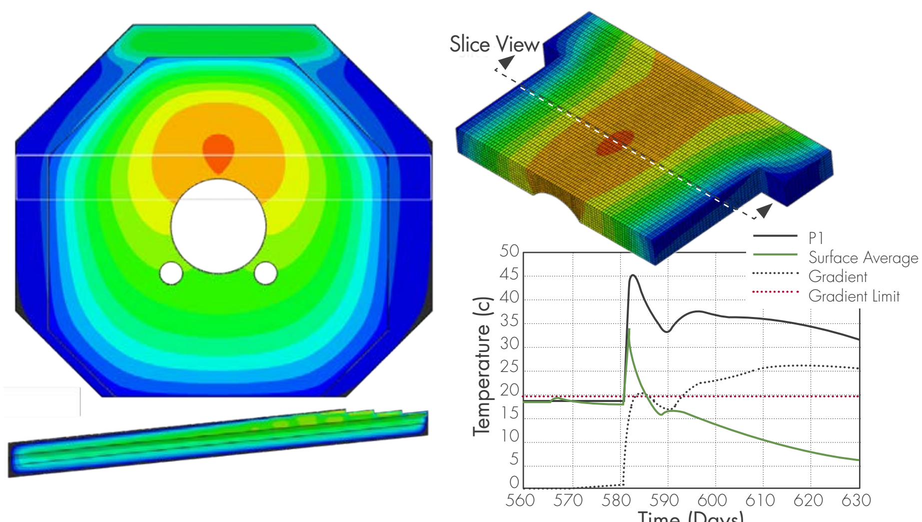

FIGURE 4. Thermal Views and Monitoring of Concrete Placement Temperatures

compare internal to external temperatures and make optimal recommendations for insulation to keep the concrete from cooling too fast.

With the thermal NISA study completed, we then coupled the thermal with the mechanical stress analysis following a similar procedure. The model was broken up into the same 164 segments, with the reinforcement separated into individual segments. As a segment was poured, its weight was first applied as pressure on surrounding segments before the segment cured enough and took load. Formwork was considered a temporary boundary condition (simulated with stiff springs): activated then removed when appropriate. The concrete internal reinforcement was activated with each concrete segment. The cycles continue with each additional segment added. The concrete material for each segment had its own values for aging, creep, shrinkage, and thermal degradation for when the concrete was placed. The effect of creep and shrinkage could be significantly different for concrete poured on the first day and concrete that is poured a year later. Mechanical tensile strain, a proxy for cracking, was plotted as shown in Figure 5.

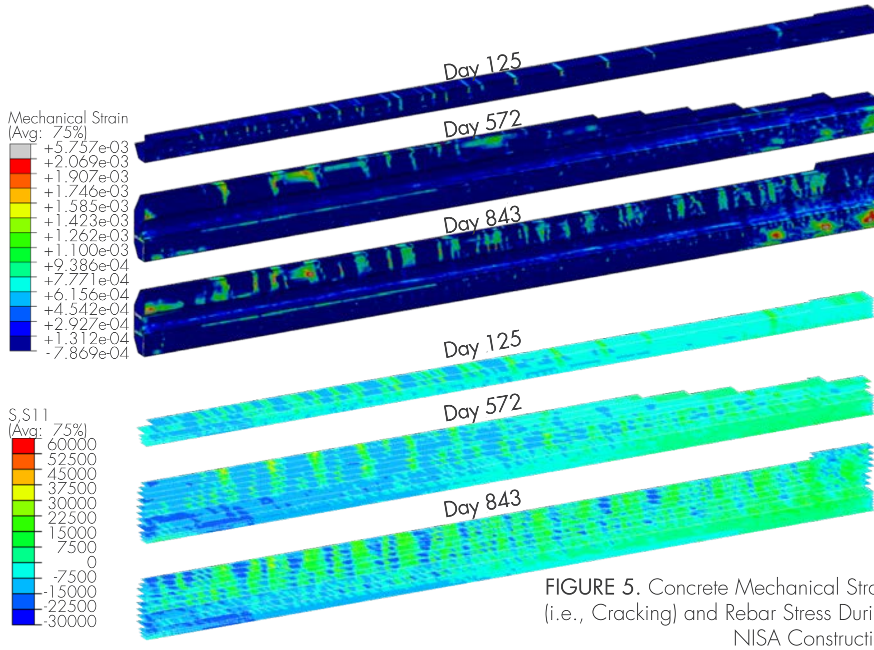

FIGURE 5. Concrete Mechanical Strain (i.e., Cracking) and Rebar Stress During NISA Construction

A critical issue of concern was the steel annulus structure at the center of the concrete tunnel. The entire steel structure was placed prior to concrete being poured around it. The steel structure was affected by the thermal and mechanical loads of each concrete pour. Structural Integrity showed this structure "breathing" as thermal/mechanical loads pass from each concrete pour into the steel structure. Armed with a complete picture from the NISA stress analysis, Structural Integrity could show the animation of annulus movement, check the out-of-roundness, and advise on reinforcement placement.

LIFECYCLE ASSESSMENTS

During the design phase, reinforced concrete structures are typically designed for a bounding range of expected loads, to include thermal load cycles, periodic live load variations, and/or vibration from mechanical equipment. Up to this point, the design phase analysis started from a "pristine" uncracked structure and applied the expected load with the beam and cooling at full power. **Seldom is the cumulative impact of cyclic loading considered for the expected service life of the structure.** Structural Integrity, having performed the NISA study, now had significantly more accurate state of the structure with expected cumulative damage already built-up. This gave us the unique opportunity to extend the analysis from the current state through the lifecycle of the structure, comparing the "pristine" to the "cumulative" case.

The expected life of the structure is 30 years of operations with the beam running for no more than nine months a year and three months off. These cycles are grouped together in either seven- or five-year blocks with a rest period of two years for maintenance or upgrades in between. The experiment starts small, ramping up the power to half the total output for the initial seven years. For the lifecycle assessment, time is still a critical element, not just for properties of concrete affected by time but the physical computational time. The transient thermal analysis would be too time intensive to run over the 30 years of life that we want to observe. To simulate the thermal cycles, the beam steady-state thermal response was calculated at each peak power level. This provided different thermal states of power, which the mechanical analysis could switch on or off as needed and interpolate between them to give a simulated ramp of power. The computational time could then be utilized on the mechanical stress lifecycle assessment.

With the completion of the lifecycles analysis, Structural Integrity could once again provide valuable information to the researchers and designers: deformations of the entire structure, deformations of the annulus, out-of-roundness of the annulus (Figure 6), estimates of crack width, etc.

> Most importantly, we can answer and show comparisons between the designed load from a "pristine" model analysis to those from the "cumulative" analysis.

Even prior to the lifecycle assessment, the cumulative damage at the end of the NISA study signaled different behavior in the expected cracking (Figure 7). From the construction process, the concrete showed cracking near the boundaries between each concrete pour. These developed due to the natural thermal cycling of the construction process. The lifecycle thermal loading continued to push and pull the structure adding to the already existing cracks. Previously, the boundary point between the fixed rail and sliding rail section concentrated the thermal loading to induce significant cracking. Now the stress will be more evenly distributed throughout the upstream section. The cracking during construction provided natural thermal breaks along the whole length of the structure.

HEAT DISPERSAL

SI then turned toward an additional question, where does all this excess heat go as the beam is cycling power? The shielding concrete is still heating up to over 60 degrees Celsius at the exposed surfaces. The air around the shielding concrete is trapped by the decay tunnel and venting conditions are unknown. We would need to produce a calculation based on the transfer of heat from the shielding concrete to the surrounding air/access tunnel, to the decay tunnel itself, and then the surrounding soil. Assuming the worst-case scenario, a point was selected along the length of the tunnel that produces maximum temperatures in the concrete. The cross section at this point is turned into a 2D model for use in a thermal analysis conducted as steady-state and transient to explore the heat transfer into the surrounding sections. A temperature profile of the decay tunnel wall was used to check its design from the thermal gradients, shown in Figure 9. The temperature of the air space between the structures can be monitored help in planning for when the tunnel can safely be accessed.

ONLINE MONITORING

Engineers at SI are always eager to add data to our models. As this structure is constructed and put into service, the actual construction and startup sequence is likely to change, allowing for the model to be rerun and the lifecycle projection recalculated. Furthermore, data from temperature sensors and crack monitoring gauges could potentially help calibrate the model based on observed conditions

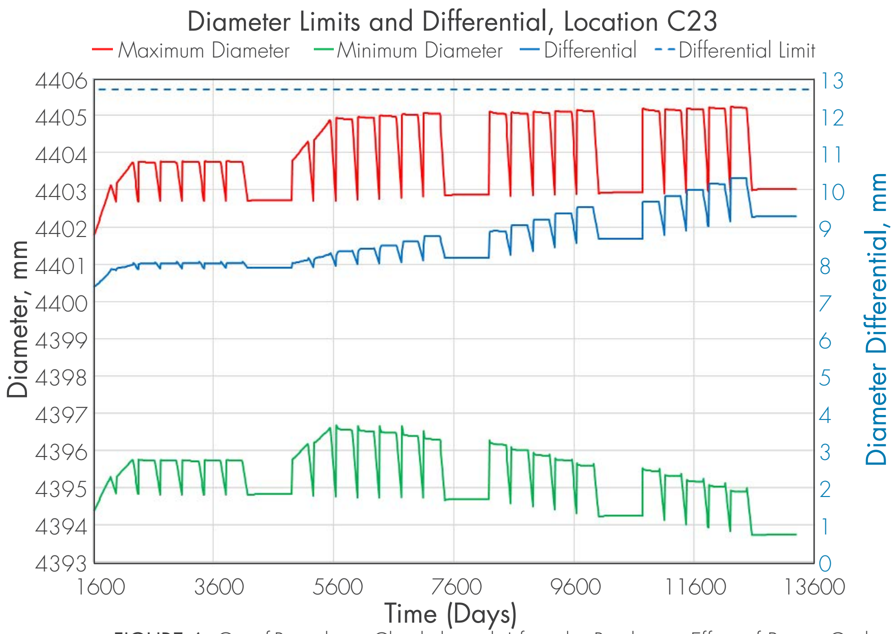

FIGURE 6. Out-of-Roundness Check through Lifecycle, Ratcheting Effect of Power Cycles

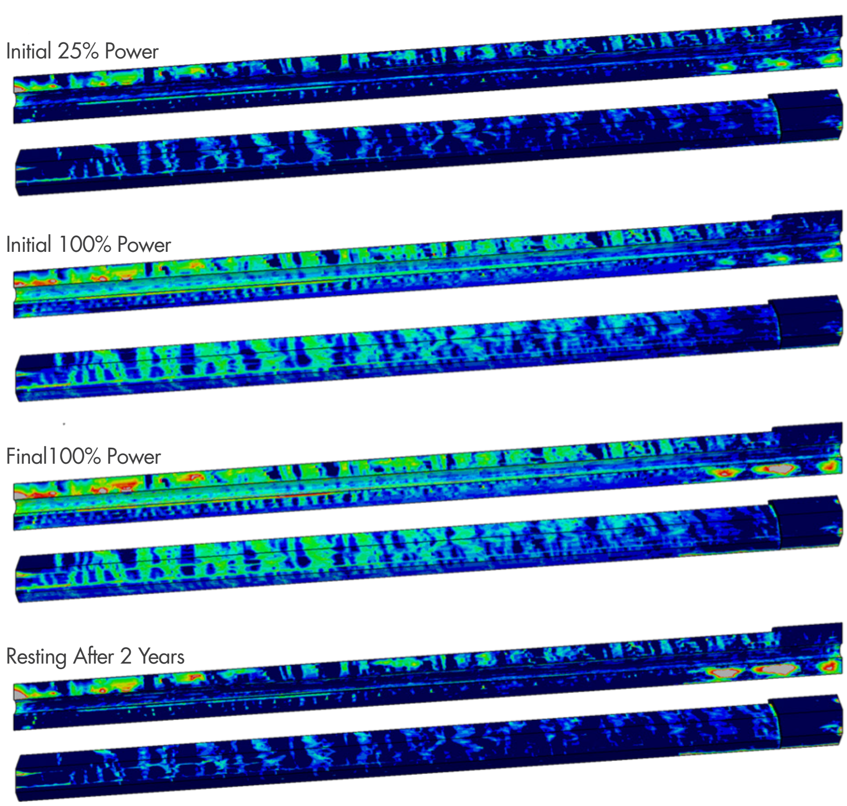

FIGURE 7. Concrete Strains at Various Point in Structures Lifecycle

to improve the accuracy of our projections moving forward. This methodology is applicable today to existing aging concrete structures where the lifecycle projection can be calibrated to existing observed conditions and data from online monitoring and non-destructive examinations.

SI demonstrated that our advanced modeling, combined with our advanced concrete model, positively influenced the design of this structure and heavily supported both the research and design teams with valuable information.

CONCLUSIONS

Structural Integrity successfully developed expanded capabilities to model thermodynamics for the energy deposition and nitrogen cooling system. SI pushed the capabilities of our concrete model to capture over 30 years of construction and operations. Along the way, SI showed that our advanced modeling, combined with our advanced concrete model, positively influenced the design of the structure, and heavily supported the design and research teams with valuable information. The robustness of the calculation showed that SI is the present and future of concrete structure analysis.

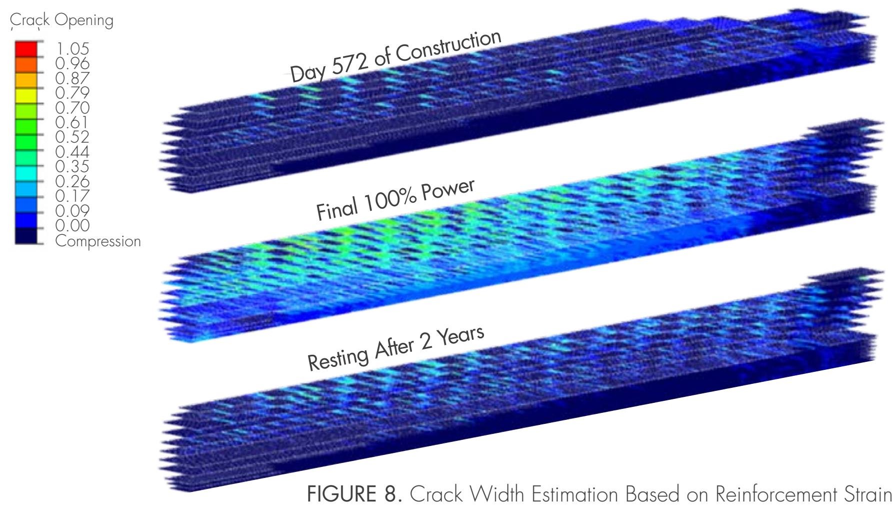

FIGURE 8. Crack Width Estimation Based on Reinforcement Strain

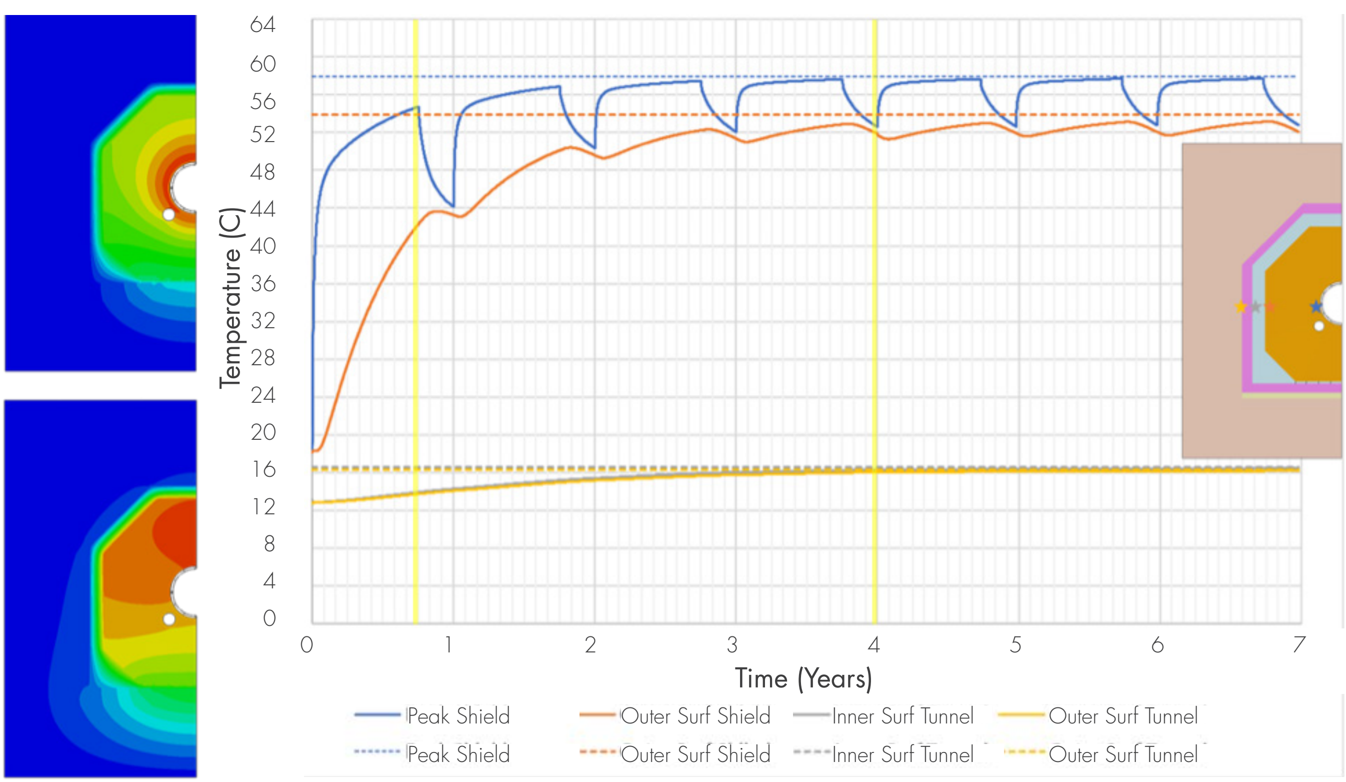

FIGURE 9. 2D Thermal Results of Decay Tunnel, Air Access Space, Shield Tunnel Walls, and Surrounding Soil

Students Showcase their Bridge Designs in Competition Organized by SI's Bend Office

Community leaders gather to glean ideas from young people for a new pedestrian bridge to connect neighborhoods.

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Becoming a professional engineer is all about knowledge and experience. Practical experience can be hard to come by, so the engineers from Structural Integrity's Bend, Oregon office sponsored a design competition for a proposed pedestrian bridge near the city's downtown. Andy Coughlin, SI's Technical Director, Critical Infrastructure, has presented guest lectures and assignments to high school engineering students at Summit High School for the last four years. The time and opportunity had come for the program and these students to get involved with the community. Andy and fellow SI employee Katie Braman began designing the competition and made a presentation to students at Summit High School.

The "Hawthorne Bridge Design Competition" took shape around a proposed pedestrian crossing in central Bend. This structure would provide safe passage across a highway and a railroad while promoting active transportation options. Most importantly, it would serve as a link from downtown to a historically marginalized area and, in turn, reinvigorate growth, housing production, and economic opportunity for residents.

To prepare for their design work, students were given information about guidelines around layouts, structural loading, design life, and structural materials and systems. They were also tasked with calculating the Benefit-Cost Ratio according to United States Department of Transportation guidelines.

Students were given eight weeks to prepare for their presentation at a partner engineering firm near the proposed bridge site. Andy and Katie organized the contest and this event, while Structural Integrity sponsored by providing students with necessary supplies and drinks and snacks for attendees. At the event, elected leaders, city staff, Oregon Department of Transportation staff, landowners, developers, transportation enthusiasts, and journalists from the Bend Bulletin were on hand for presentations from the students. Following the presentations, the group walked to the nearby proposed construction site to

FIGURE 1. Summit High School students gather with community leaders from the City of Bend, Bend Parks, and the Oregon Department of Transportation for a design showcase event organized by SI's Bend Office

further the conversation and document existing conditions. We are proud to note that engineers from the structural firm charged with the feasibility study were also in attendance at the event; their designs presented to Bend officials on a later occasion prove that the student's presentations were, in fact, influential as visible in the firm's proposal.

At Structural Integrity, one of our core values states, "SI Will Be a Role Model in Corporate Citizenship." Our ongoing mentorship of the engineering students in the Bend community exemplifies our commitment to that end, and it's fun and rewarding too. We look forward to these students' bright future and are proud to be part of their educational experience.

FIGURE 2. SI's Andy Coughlin (LEFT) and Katie Braman (second from left) with high school students (MIDDLE AND SECOND FROM RIGHT) and James, a community transportation enthusiast (right)

Pedestrian and Bike Crossing at NW Hawthorne Ave.

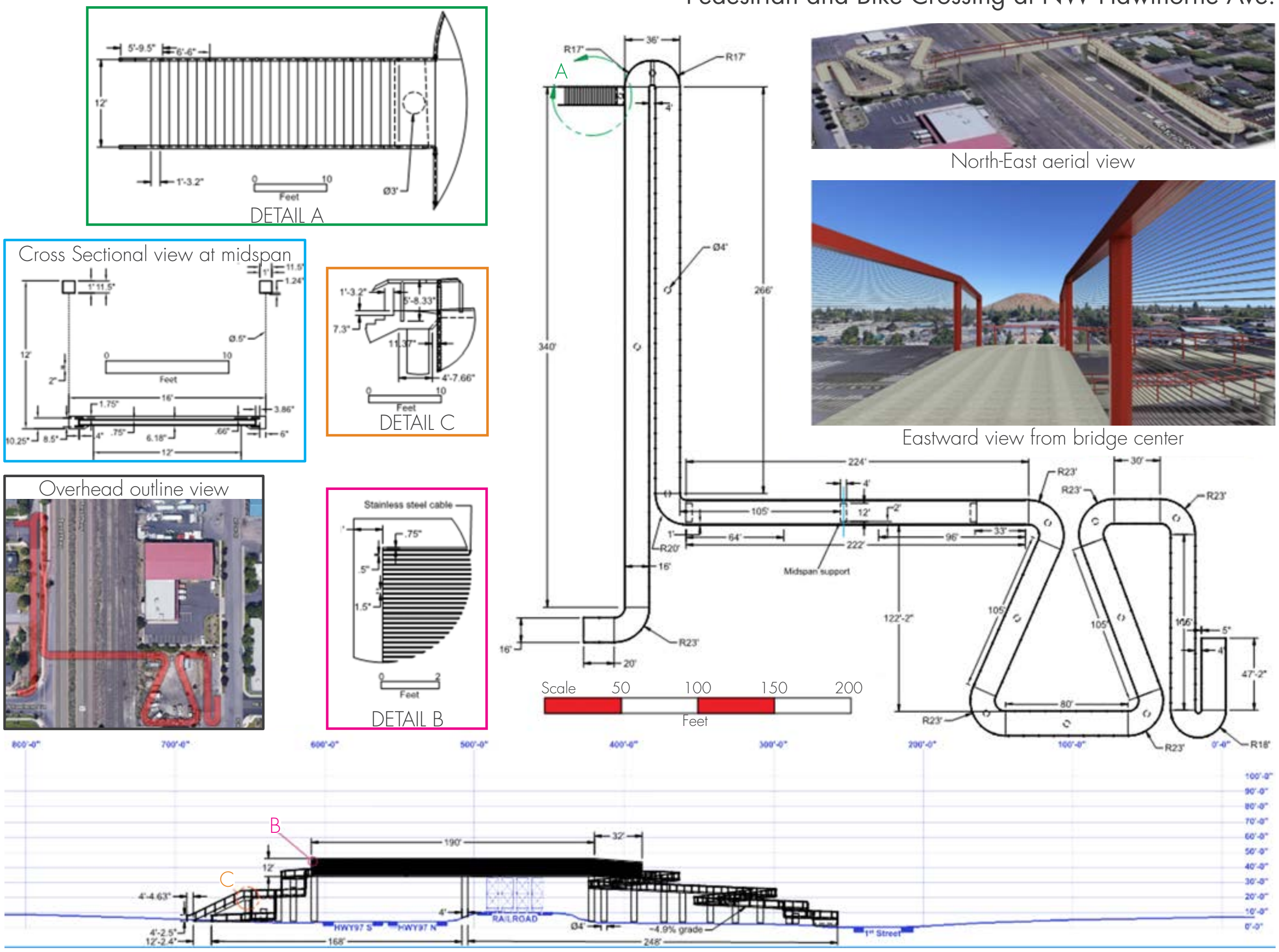
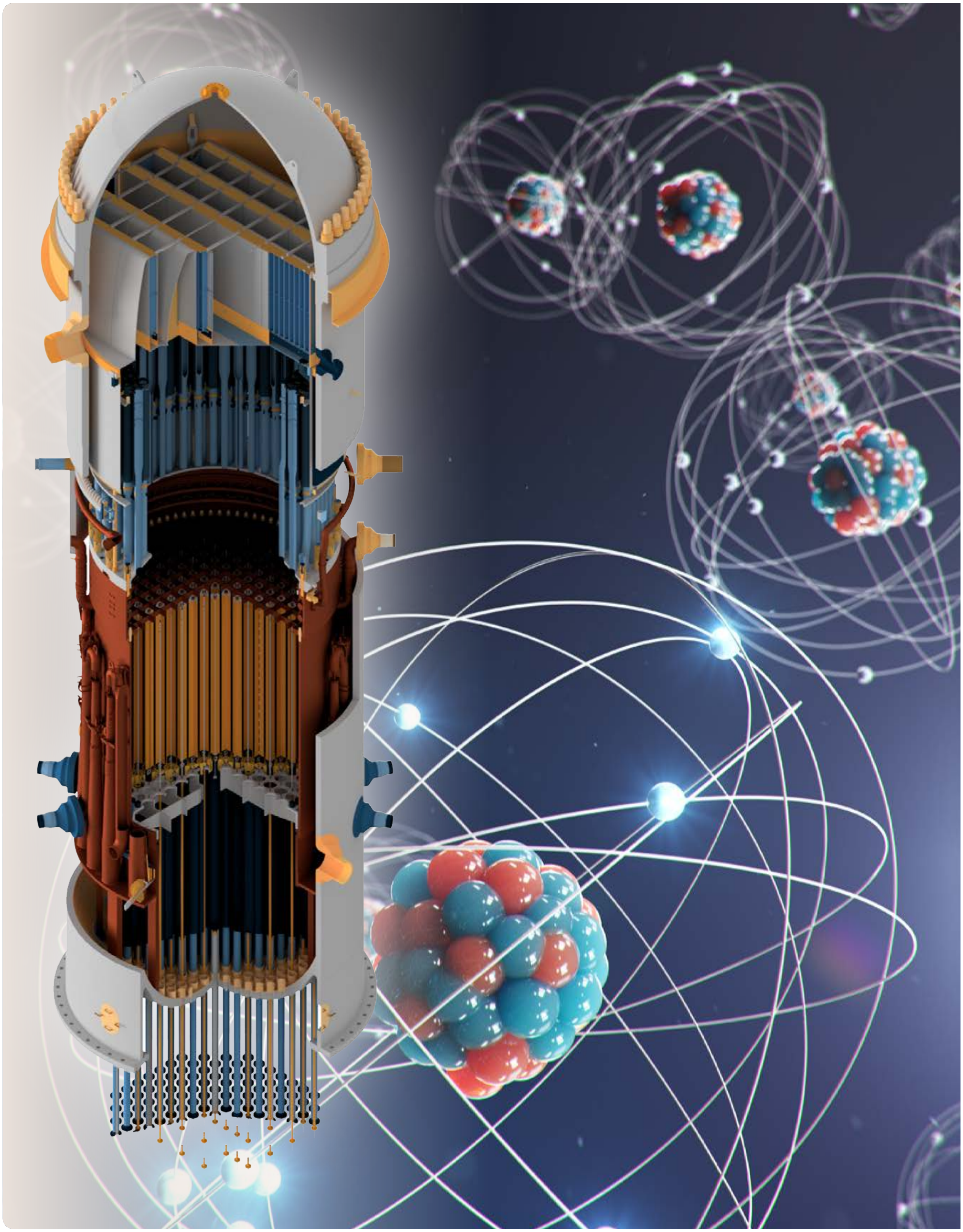


FIGURE 3. Example Bridge Design from Summit High School Student (COURTESY DJANGO WARDLOW)



Modernization of a Hydrogen Water Chemistry Injection System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The implementation of modern automation optimizes system performance, reduces maintenance and operator intervention, and reduces hydrogen water chemistry (HWC) trips and the resulting crud bursts. The return on investment is significant.

In a Boiling Water Reactor (BWR), asset protection is normally achieved through the combination of online noble chemistry (OLNC) and hydrogen water chemistry (HWC). Mitigation of intergranular stress corrosion cracking (IGSCC) at many nuclear power stations, including the Limerick Generating Station, is accomplished by feedwater hydrogen injection in conjunction with noble metal technology using the Online NobleChem™ (OLNC) process. The feedwater hydrogen injection systems at Limerick was commissioned in 1998 – 24 years ago. While OLNC applications are annually performed at a BWR, hydrogen water chemistry (HWC) is accomplished through the continuous injection of hydrogen into the feedwater system. The loss of HWC, often referred to as an HWC trip, will cause a change in reactor water chemistry that can negatively impact asset protection due to a resultant crud burst consisting of insoluble iron and other insoluble species and a rise in reactor conductivity. A trip of the HWC system also negatively impacts the station's hydrogen availability score/ marker, which is a component required for inspection relief during a refueling outage. High hydrogen availability (>99%) for an operating cycle maximizes asset protection and saves outage time by qualifying the station for inspection relief of vessel internals and components.

Most of the U.S. nuclear fleet plants operate with obsolete automation equipment and technology.

Continued on next page

According to the U.S. Energy Information Administration (EIA), the average age of the U.S.- based nuclear power plant is approximately 40 years old. While the original equipment and technology have served well, the digital age has demonstrated that today's automation equipment is considerably more reliable than its predecessors. In an industry that demands and achieves high reliability, it is important to replace obsolete equipment to address system reliability issues and inefficiencies that burden both Operations and Maintenance resources.

The original HWC system (Figure 1) had been operating for over 20 years. It contained obsolete components not readily available from the OEM and only available via the secondary market. In addition, the old panels had experienced multiple trips due to their failing, unreliable components. These failures created a vulnerability from the downtime that challenged both the station and Constellation asset protection goals. Maintaining the system had become a challenge to the station due to the obsolescence of both the control panel components and the associated automation software.

In December 2019, Structural Integrity’s Chemistry Group was contracted by Exelon (now Constellation) for the design and fabrication of a replacement control panel (Panel C177) for the Limerick Generating Station hydrogen water chemistry (HWC) control system at both Units 1 & 2. The Unit 2 installation was scheduled for May 2021 during the Unit 2 refueling outage, and the Unit 1 installation was scheduled for April 2022 during the Unit 1 refueling outage.

The replacement control panels designed and fabricated by Structural Integrity included a state-of-the-art programmable logic controller (PLC) with two stand-alone human-machine interfaces (HMIs). Although the replacement control system retains the original system's basic operational functions, the upgraded design incorporates additional operational features and flexibility based on Structural Integrity's prior design experience. Additionally, virtual flow controllers were incorporated into the PLC/HMI design replacing physical panel-mount controllers. This not only eliminated the main source of the original system's maintenance/availability issues but also provided the flexibility to allow system operation with either air or oxygen injection when desired. Structural Integrity worked closely with our fabricator, Advanced Industrial Controls (AIC), to meet the design requirements set by Limerick Generating Station.

The state-of-the-art automation system utilizes the Allen-Bradley ControlLogix PLC platform (Figure 2) in combination with dual Allen-Bradley Human Machine Interface (HMI) industrial workstations operating in the Windows® environment (Figure 3). The HMIs are configured to operate independently of each other, thus providing increased system reliability in the event of a single workstation failure.

FIGURE 1. Previously Installed HWC Panel at Limerick Unit 2 (Front Panel Face)

The associated HMI graphics application programs (Figure 4) and PLC ladder logic were both developed in-house by Structural Integrity. Utilizing the Chemistry Group’s extensive experience with HMI graphics, PLC ladder logic, and system panel upgrades; the various modes of operation for the HWC system were incorporated in a manner that focused on error prevention techniques, live time trending, and monitoring of system parameters, and system flexibility that allows Operations’ supervisors to address degraded field equipment through the disabling of system trips. In addition, the design incorporated feedback to address expanded operational control features. Most notable is the ability of maintenance technicians and Operations supervisors to fine-tune the control system configuration directly through the HMI workstation. As part of extensive factory testing, operator feedback was collected about the current approach to HWC system train swaps and the challenges, including the requirement of operating multiple valves via panel-mount switches simultaneously. A collective approach was developed and implemented that enabled HWC system train swaps to become part of the automation controls and eliminate a likely error situation for operators.

The outage work for the HWC control system at Limerick included the complete removal and replacement of the original HWC control panel with the all-new Structural Integrity panel, followed by startup testing. The HWC system is required to be in service as part of the plant startup procedure; any delays in the installation and testing schedule would have resulted in a loss of hydrogen availability that could challenge startup requirements. To avoid delays, Structural Integrity performed weeks of extensive factory testing before the 2-day factory acceptance demonstration test of the Unit 2 HWC Control Panel at AIC, observed by six (6) individuals from the Limerick Generating Station modification team. Minor enhancements were identified and addressed before the shipment of the Unit 2 panel for installation.

Additionally, to verify that the supplied automation control system would work as designed with minimal field revisions, Structural Integrity built a desktop simulator system (Figure 5) that replicated the new HWC control system functionality.

FIGURE 2. Allen-Bradley PLC (ControlLogix Platform)

FIGURE 3. Limerick Unit 1 HWC Control System Arrangement

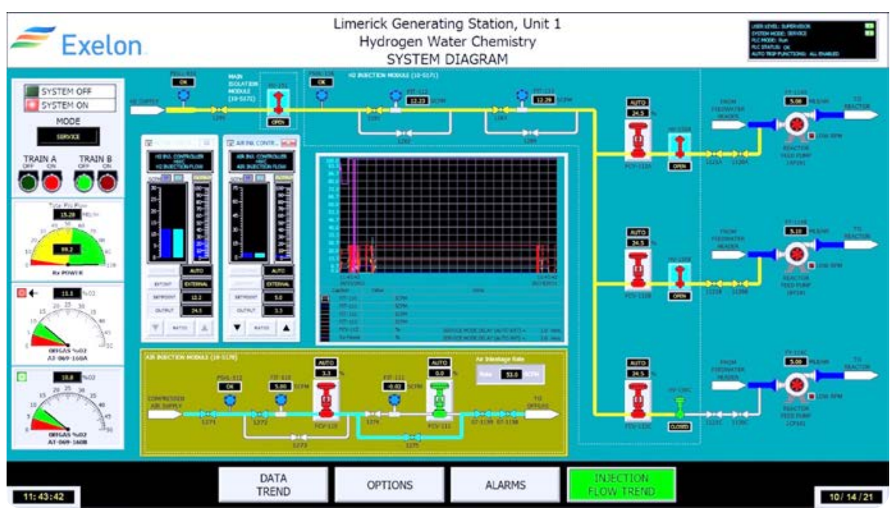


FIGURE 4. Limerick Unit 1 HWC System - HMI Software Application Graphics

FIGURE 6. Limerick Unit 2 HWC Panel Installed

> The desktop simulator was utilized by Structural Integrity to develop and challenge the PLC and HMI software applications and later develop and test station requested enhancements and modifications following the Unit 2 installation.

The installation at Unit 2 (Figure 6) was performed with no delays. Support was provided by the Structural Integrity Team around the clock for nine days despite other station equipment challenges that delayed the reactor startup. During its first few months in service, the Unit 2 system experienced several system trips that immediately led to a collaborative troubleshooting effort between Structural Integrity and the Limerick station. The cause was identified as a degraded network switch component, which was replaced along with all Ethernet cables that restored the HWC Control system to the as-expected operating condition.

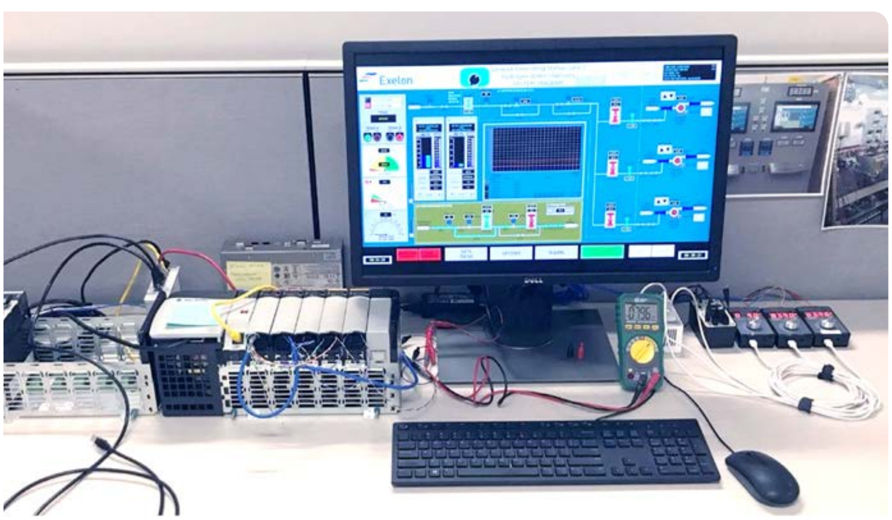


FIGURE 5. Limerick Unit 2 HWC Control Desktop Simulator System

Lessons learned from the Unit 2 fabrication, testing, installation, and additional enhancements requested by the station were incorporated into the Unit 1 HWC Control Panel. The collaborative effort between Structural Integrity Associates, AIC, and the Limerick Generating Station delivered a Unit 1 HWC Control Panel that resulted in an exemplary factory acceptance test with no follow-up actions. Installation at Unit 1 in April 2022 (Figure 8) went smoothly and resulted in the HWC Control Panel being ready for operation at the beginning of the startup window. This project's accurate and timely execution demonstrates the quality and value that Structural Integrity delivers to its clients.

The success of the Limerick HWC control system upgrade for both Units 1 & 2 builds upon the positive and impactful relationship Structural Integrity has built with Constellation following the successful upgrade of the Reactor Water Cleanup (RWCU) System Control Panels at Nine Mile Point Unit 2 (2021-2022) and FitzPatrick (2018). Future Structural Integrity / Constellation projects include upgrading their Fuel Pool Filter/Demineralizer control systems at the Quad Cities Station. Additional Constellation stations and other utilities have inquired about RWCU and HWC control panel upgrades following the

FIGURE 7. Limerick Unit 2 HWC Control System Arrangement

positive feedback that demonstrated improved performance and monitoring ability provided by Structural Integrity.

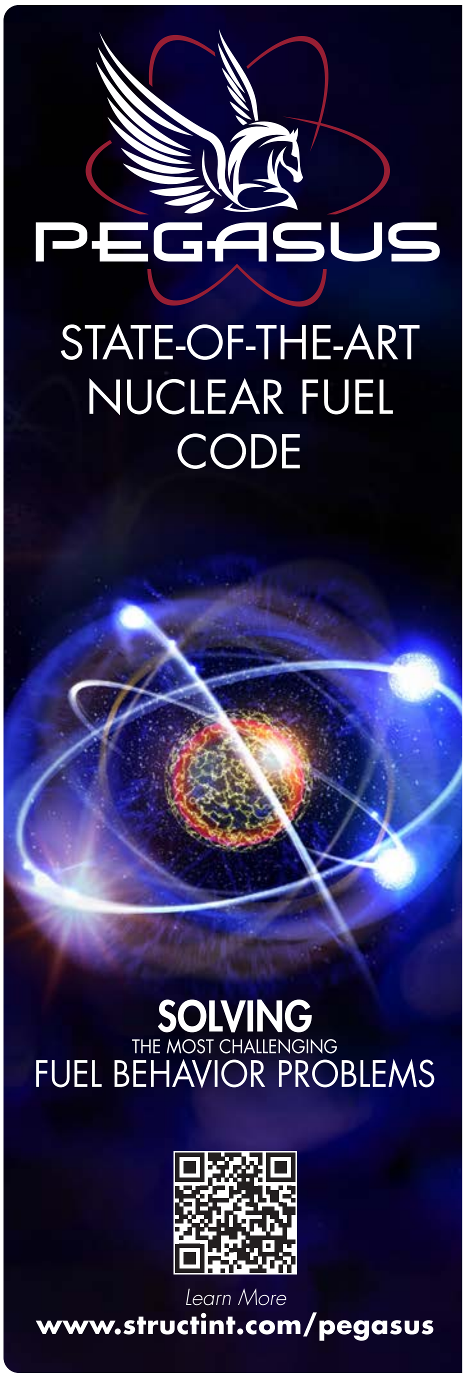
Structural Integrity completed the project on time resulting in zero additional plant downtime thanks to diligent preparation and collaboration with the team at Limerick. The SI team reacted swiftly in addressing requested enhancements and hardware issues following Unit 2 becoming operational and subsequently integrated learnings towards the design and installation of Unit 1. The HWC systems at Limerick are operating more efficiently thanks to thanks to the increased operational information the HMIs provide, along with the improved operational flexibility of the automation system that allows Operations supervisors to address degraded field equipment through the disabling of costly, unnecessary system trips. Want to reduce operations and maintenance issues associated with your HWC system? Contact SI to see how we can help.

FIGURE 8. Limerick Unit 1 HWC Control System – HMI and O/I

FIGURE 9. Before and After HWC Panels at Limerick Generating Station

PEGASUS

Development for TRISO Fuel and Advanced Reactor Applications



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The PEGASUS code allows the user to develop more realistic models of fuel behavior by utilizing an innovative 3D framework that delivers a more detailed and rigorous solution. This solution allows the user to remove conservative assumptions, simplifications, and uncertainties resulting from 2D or 1D simplified/empirical solutions.

Remove the conservativism and start using the calculated operational margins to increase efficiencies and reduce the capital outlay for refueling.

QUICK FACTS

- Independently developed 3D FEM code; fuel vendor independent code provides best-estimate performance modeling
- Focused on fuel structure
- Provides high-fidelity results
- Addresses existing fuel performance
- Aids in the development of advanced fuel designs
- Ready for Gen IV Reactors and TRISO Fuels

BENEFITS REALIZED

- Reduced conservatism
- Increased efficiencies
- Potential for significant fuel cost savings

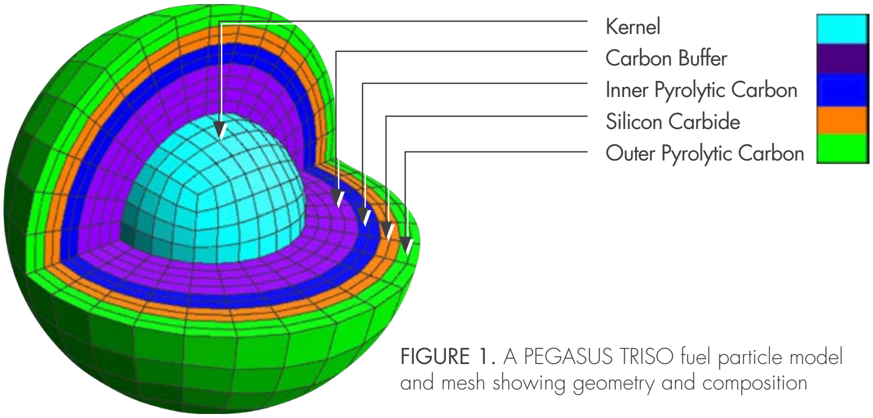


FIGURE 1. A PEGASUS TRISO fuel particle model and mesh showing geometry and composition

INTRODUCTION

The PEGASUS nuclear fuel behavior code is a robust 3D, finite element modeling (FEM) computational software platform capable of thermo-mechanical and structural non-linear analyses of nuclear fuel and reactor components. Focused initially on light water reactor (LWR) fuels and materials, PEGASUS is being adapted and applied to a broader range of emerging industry priorities for proposed Gen IV (Generation IV) advanced reactor designs such as high-temperature gas (HTGRs) and molten salt-cooled reactors (MSRs). These applications require modeling various fuel forms, geometries, and materials such as high assay, low enrichment uranium (HALEU), advanced cladding alloys, and other fuels with integrated containment such as tri-structural isotropic (TRISO) fuel particles and encapsulated particle fuel types. PEGASUS is perfectly positioned to evaluate these challenging structures with realistic modeling and simulation results.

> Material constitutive models have been developed for UCO fuel, porous and pyrolytic carbon, and SiC and are currently being tested for application in PEGASUS.

TRISO-BASED FUELS AND MATERIALS DEVELOPMENT

One of the significant efforts underway in the continued development of PEGASUS is the introduction of material constitutive and behavioral models for TRISO fuel and the materials that comprise this fuel form. The initial research on the needed material property and behavior model data comes from a variety of sources, including the Department of Energy's (DOE's) Advanced Gas Reactor (AGR) fuel development and qualification experimental program [1] and numerous DOE-supported modeling efforts such as those from Hales et al. [2,3]. In parallel to those efforts, geometric modeling and meshing techniques specifically designed to address the complex TRISO fuel geometric configurations are being explored and developed. These exploit the CAD-like modeling environment and the already available automated meshing tools and capabilities in PEGASUS.

TRISO fuel forms are comprised of multi-layered particles embedded into fuel compacts of various compositions and shapes. The TRISO particle layers are designed to encapsulate and contain the nuclear fuel and the fission products produced during operation. It is this characteristic that creates the robust nature of TRISO-based fuels. The fuel particles are typically composed of a fuel kernel, such as uranium oxycarbide (UCO), surrounded by layers of 1) a porous carbon buffer, 2) an inner pyrolytic carbon (PyC) shell, 3) a silicon carbide (SiC) layer, and 4) an outer PyC shell. The orientation and relative thicknesses of these layers are shown in Figure 1, which depicts a basic PEGASUS TRISO particle model.

TRISO FUEL CONFIGURATIONS AND MODELING DEVELOPMENT

In addition to conventional FEM-based modeling and meshing capabilities, PEGASUS also contains several tools explicitly designed to facilitate advanced reactor and fuel analysis. These include: 1) a 3D and hybrid 2D/3D meshing capability to optimize computational efficiency (currently under development), 2) a "spherical mesh object" tool to generate 3D/2D spheres and embedded spheres for modeling TRISO and fully encapsulated TRISO fuel forms, and 3) a "spiral extrusion" tool which can generate complex, spiral 3D fuel geometries and meshes such as those required for helical multi-lobed advanced fuel designs.

> The spherical mesh object and spiral extrusion tools are unique to PEGASUS and, to our knowledge, not found in any other fuel performance or general-purpose FEM code.

These modeling capabilities allow PEGASUS to be used to investigate very detailed mechanical and structural effects in highly complex fuel forms. For example, the mechanical interaction between TRISO fuel layers, including the effects of cracking, debonding, and asphericity, can be modeled explicitly. Future work is planned to integrate damage-mechanics modeling capability into PEGASUS that is specifically applicable to TRISO-based fuels.

Given the complexity of typical TRISO fuel forms, another critical aspect for analysis is the development of a consistent methodology for generating configurations that mimic the distribution of TRISO particles in a fuel matrix. A technique has been developed based on a "passive randomization method" originated by Sukharev [4] that yields distribution patterns approximating those of TRISO fuels observed during fuel examinations. An example of an early application of this technique is shown in Figure 2, which compares a fuel micrograph to a generated TRISO particle

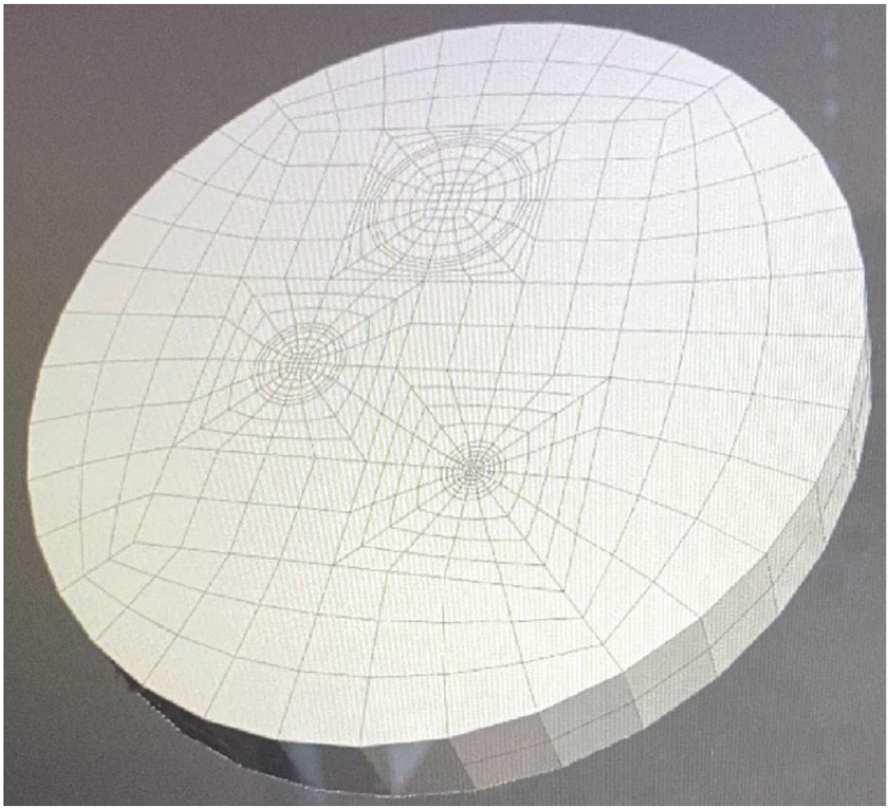
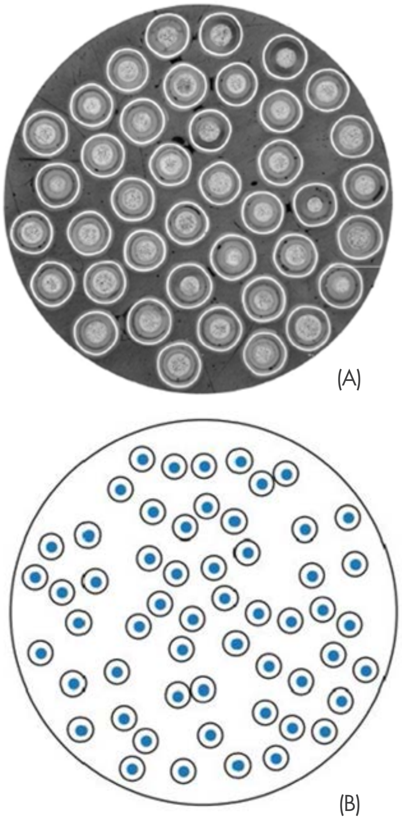


FIGURE 3. Cross-sectional view of embedded TRISO particles in a 3D fuel compact matrix.



For application in PEGASUS, geometric configurations such as shown in Figure 2b are converted into 2D and 3D FEM meshes with TRISO kernels embedded in meshed substrates using automated tools. Models such as these can provide the bases for computational studies of TRISO fuel performance, from detailed kernel multilayer response to interactions between multiple kernels and their surrounding matrix. Several examples of TRISO meshes generated with PEGASUS are shown in Figures 3, 4, and 5. Figure 3 illustrates the cross-section of a 3D TRISO fuel compact with embedded TRISO particles. The appearance of multiple particle sizes is an indication of varying particle depths within the matrix. This figure was generated using the spherical object meshing tool in PEGASUS.

FIGURE 2. Example TRISO particle distribution: (A) micrograph of a TRISO fuel compact (adapted from Nelson [5]), (B) random particle distribution pattern algorithm output.

A more complex 3D model of encapsulated TRISO particles is shown in Figure 4. This model features a sparse particle distribution generated using the randomization technique applied in Figure 2b coupled with 3D automated meshing capabilities. This model was meshed in PEGASUS using an automated scripting tool and tested early in the development project using simplified approximations of thermal and mechanical properties of the kernel and matrix materials. Boundary conditions simulating prototypic gas reactor conditions were used in the simulation. Figure 5 shows the plotted temperature distribution from a portion of the model in figure 4.

Further development of the TRISO fuel modeling capabilities in PEGASUS is ongoing. Detailed 3D modeling of TRISO kernels with irregular geometries such as non-uniform thicknesses and shapes in

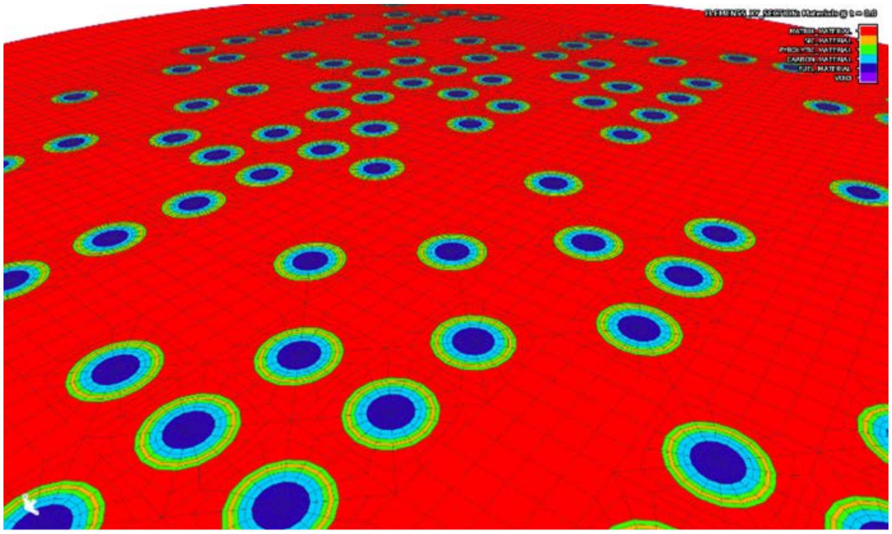


FIGURE 4. Cross section of an array of discrete 3D TRISO particles embedded into a graphite compact pellet.

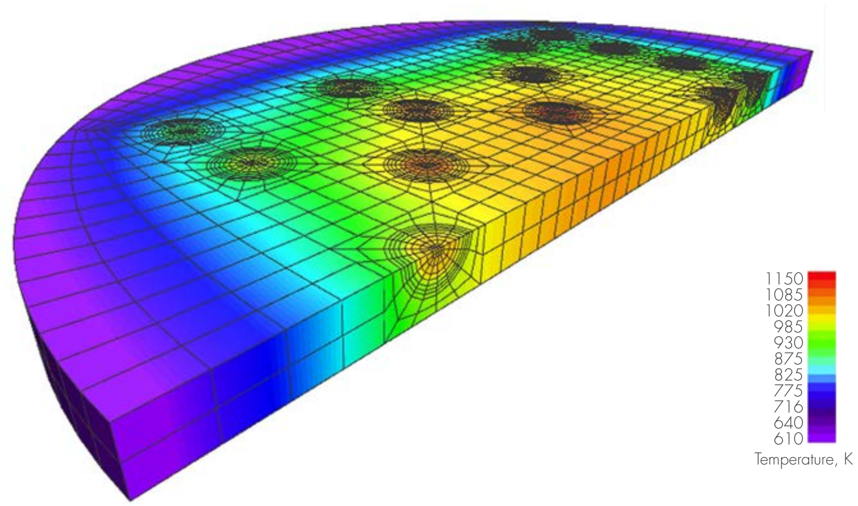


FIGURE 5. Temperature distribution in a cross-section of a 3D slab of a TRISO compact matrix model under prototypic gas-cooled reactor conditions.

the pyrolytic carbon and SiC layers has been identified as a high priority as we advance. Additional priorities for future development include 1) implementation of mechanistically based, deterministic TRISO kernel and fuel compact failure models integrated into the material constitutive relations and 2) the calculation and tracking of fission product species diffusion and concentrations which incorporate the effects of chemical interactions, kernel layer, and substrate cracking.

SUMMARY

The PEGASUS nuclear fuel behavior code is an advanced, independently developed 3D FEM computational software program capable of conducting complex, coupled thermo-mechanical and structural non-linear analyses. The role of PEGASUS is envisioned as complementary to existing regulatory-based assessment and licensing tools, where there is a need to address conservatism, perform an independent assessment, or provide additional fidelity to laboratory-sponsored research where wider materials, phenomena, or fidelity is needed. Current development activity is focused on application to proposed GEN IV advanced reactor designs featuring unique fuel materials and design configurations such as TRISO-based ceramic fuels to be deployed in HTRGs and MSRs. Future development work on PEGASUS will continue along multiple avenues, emphasizing TRISO constitutive and deterministic failure model development, implementation, and modeling. In summary, PEGASUS provides high fidelity and independent advanced analysis capability that can be used to address existing fuel performance. It allows for less conservatism and accelerates the development, design, and regulatory processes for new fuel concepts and advanced fuel designs such as those employing TRISO-based fuels.

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[3] J. D. HALES et al. "BISON TRISO Modeling Advancements and Validation to AGR-21 Data," INL/EXT-20-59368, September 2020.

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[5] A. T. NELSON, Features that Further Performance Limits of Nuclear Fuel Fabrication: Opportunities for Additive Manufacturing of Nuclear Fuels, ORNL/SPR-2019/1183, May 2019.

An SIIQ™ Primer

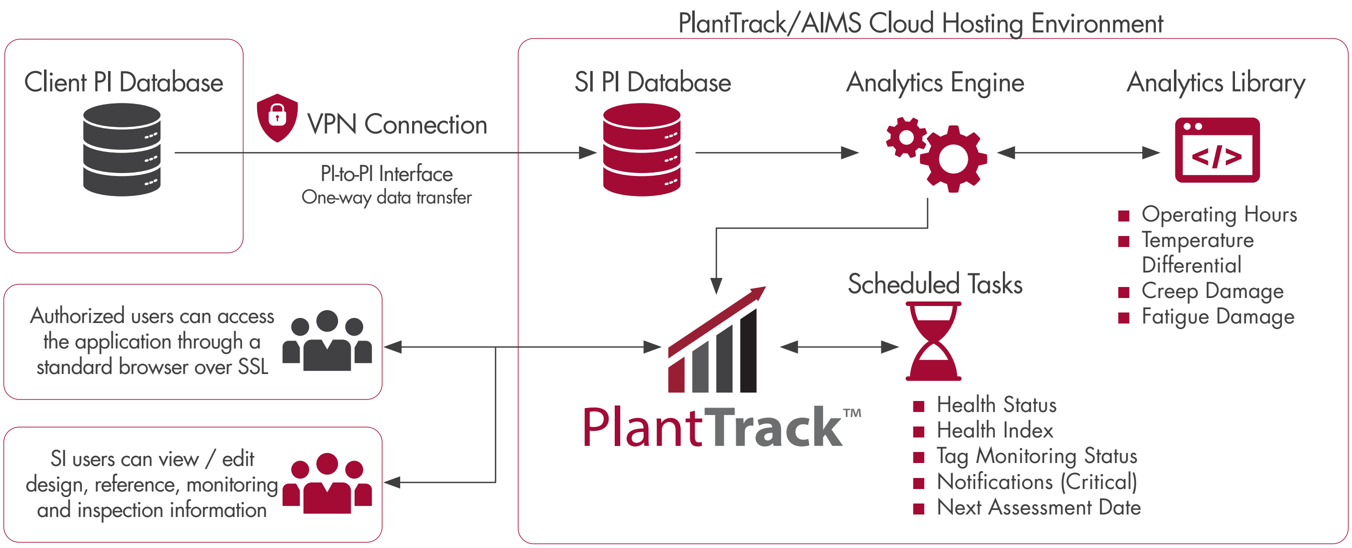

FIGURE 1. Typical architecture for connection to data historian.

SI's technology differs from most systems by focusing on **modeling of damage mechanisms** (e.g. damage initiation and subsequent rate of accumulation) affecting components that, if a failure were to occur, would impact safety and reliability.

SIIQ™ is part of the next-generation approach for managing assets through online monitoring and diagnostic (M&D) systems. The advancements in sensor technology, signal transmission (wired or wireless), data storage, and computing power allow for ever more cost-efficient collection and analysis of 'Big Data.'

The online monitoring module of SI's PlantTrack™ data management system can retrieve operating data from OSIsoft's PI data historian (or other historians, for that matter – see below for typical architecture). Access to data from the historian is critical for moving beyond the stage of detecting adverse temperature events from the local surface-mounted thermocouples. Examination of pertinent data from select tags (as seen in Figure 3 of the article beginning page 29) is reviewed by SI experts to help derive a more optimal solution to mitigate further events. The benefit of the real-time monitoring is to detect improper operation and diagnose prior to damage progressing to failure. Continuously monitoring the condition allows for early remediation and potentially avoiding a failure that would result in loss of unit availability and possible personnel injury. Further, if monitoring indicates no issues are occurring, it may justify deferring a costly inspection.

Online Monitoring of HRSG with SIIQ™

A Case Study on Implementation at a 3x1 Combined Cycle Facility (Article 1 of 3)

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SI has successfully implemented a real-time, online, damage monitoring system for the Heat Recovery Steam Generators (HRSGs) at a combined cycle plant with a 3x1 configuration (3 HRSGs providing steam to a single steam turbine). The system is configured to quantify and monitor the life limiting effects of creep and fatigue at select locations on each of the HRSGs (e.g. attemperators, headers, and drums – see Figure 1). The brand name for this system is SIIQ™ , which exists as a monitoring solution for high energy piping (HEP) systems and/or HRSG pressure-part components. SIIQ™ utilizes off-the-shelf sensors (e.g. surface-mounted thermocouples) and existing instrumentation (e.g. thermowells, pressure taps, flow transmitters, etc.) via secure access to the data historian. The incorporation of this data into SI's damage accumulation algorithms generates results that are then displayed within the online monitoring module of SI's PlantTrack™ data management system (example of the dashboard display shown in Figure 2).

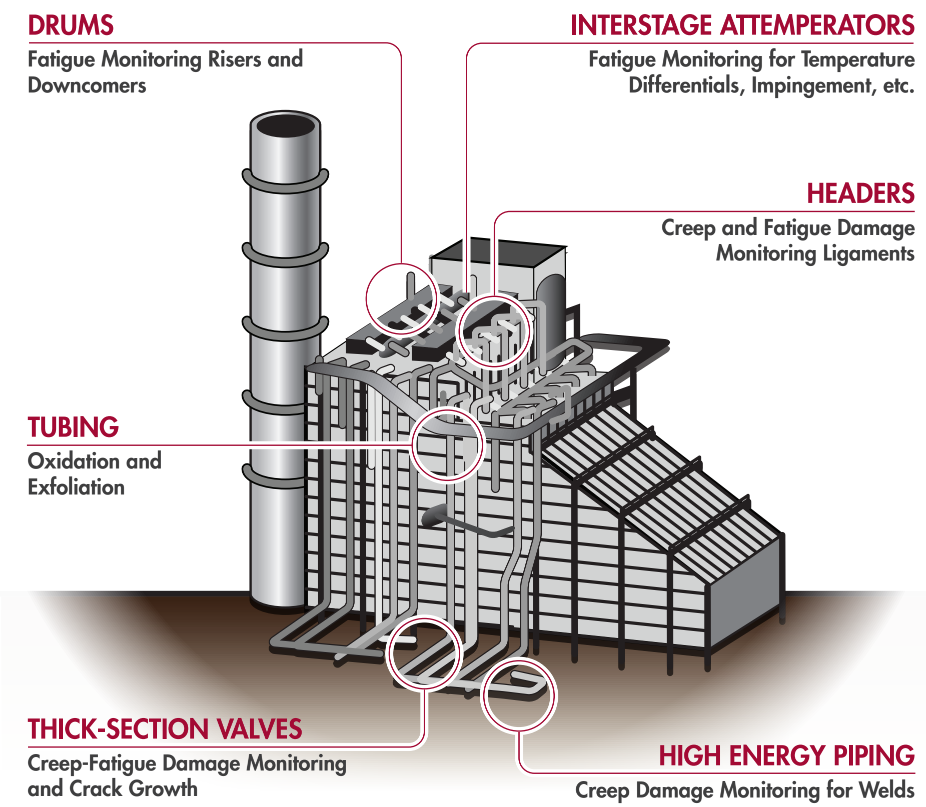
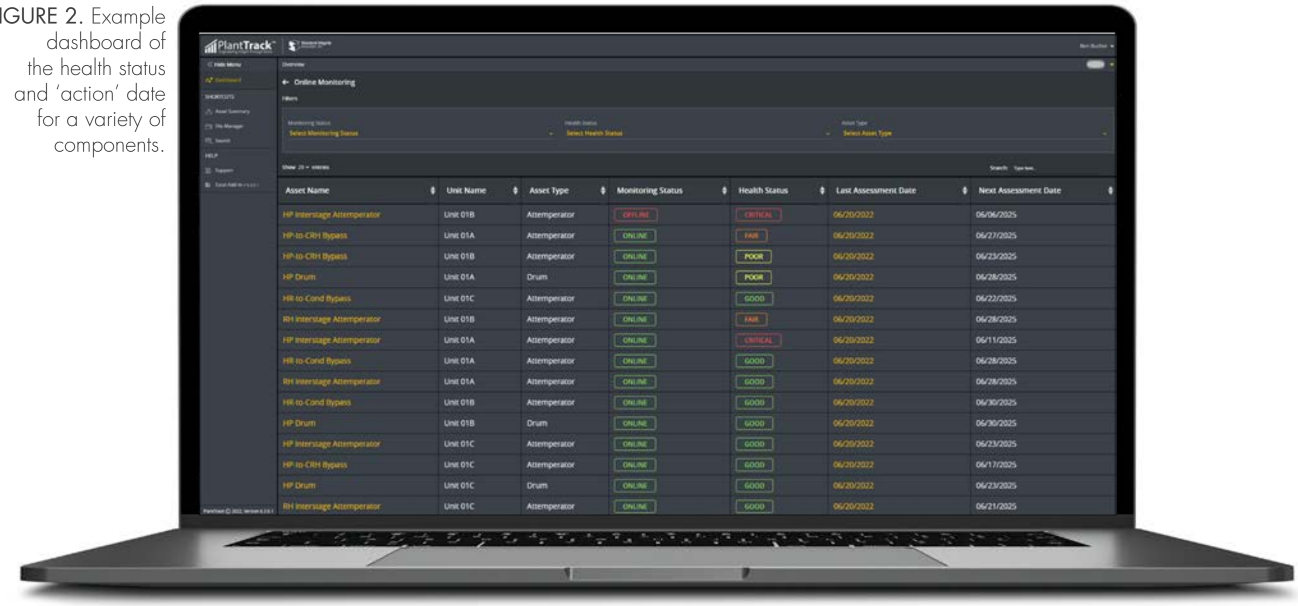


FIGURE 1. Typical components that are monitored with the pertinent damage mechanisms in mind.

FIGURE 2. Example dashboard of the health status and 'action' date for a variety of components.



This article will be part of a series discussing items such as the background for monitoring, implementation/monitoring location selection, and future results for the 3x1 combined cycle plant.

- **Article 1** (current): Introduction to SIIQ™ with common locations for monitoring within HRSGs (and sections of HEP systems)
- **Article 2**: Process of SIIQ™ implementation for the 3x1 facility with a discussion of the technical foundation for damage tracking
- **Article 3**: Presentation of results from at least 6+ months, or another appropriate timeframe, of online monitoring data

BASIS FOR MONITORING

The owner of the plant implemented the system with the desire of optimizing operations and maintenance expenses by reducing inspections or at least focusing inspections on the highest risk locations. The system has been in place for a few months now and is continuously updating risk ranking of the equipment and 'action' intervals. The 'action' recommended may be operational review, further analysis, or inspections. This information is now being used to determine the optimum scope of work for the next maintenance

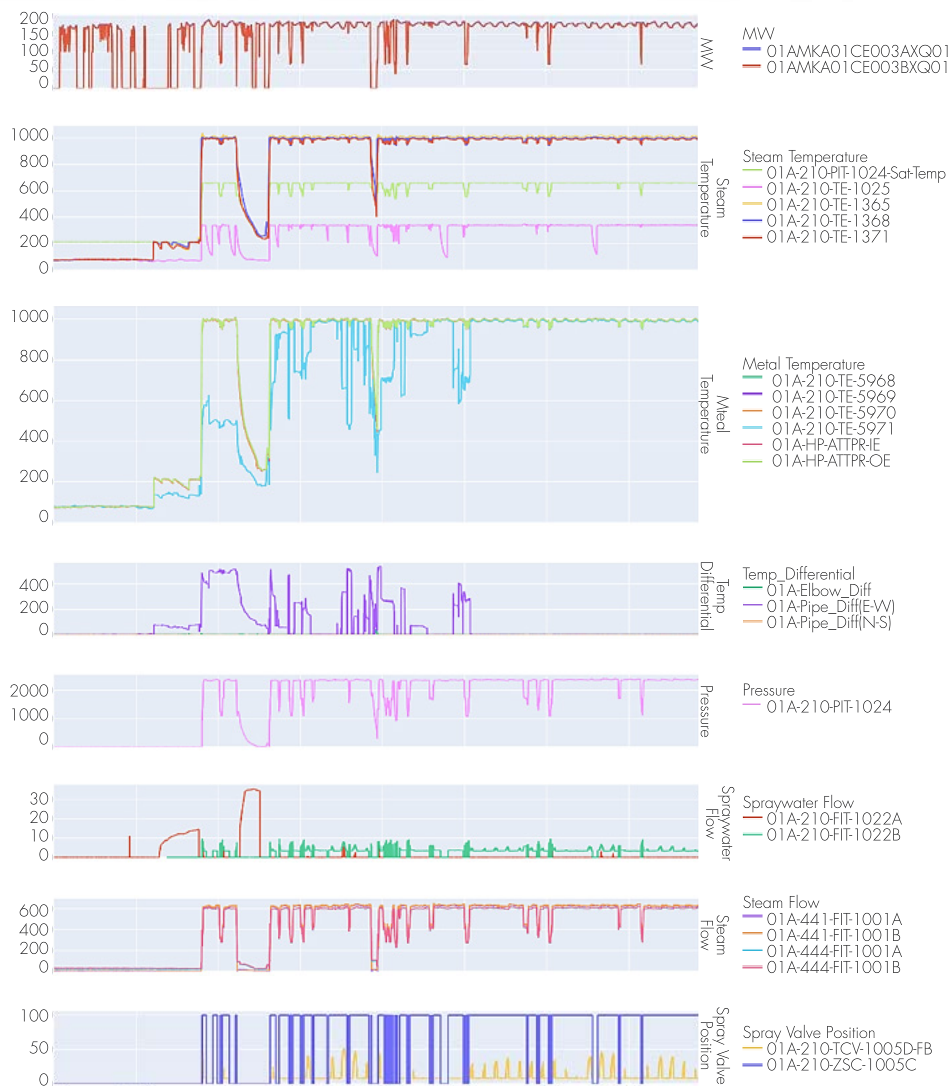
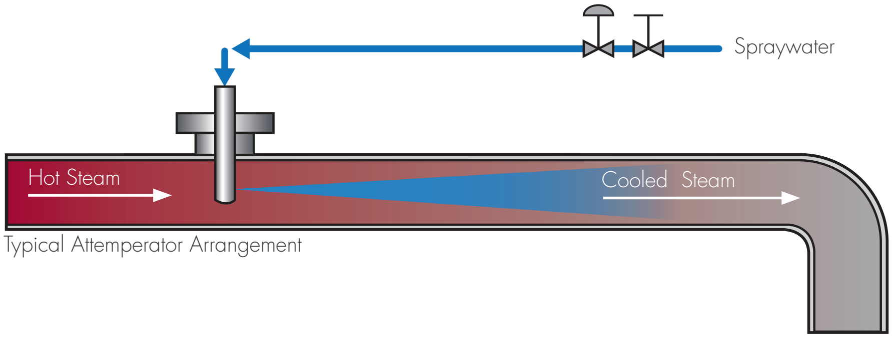
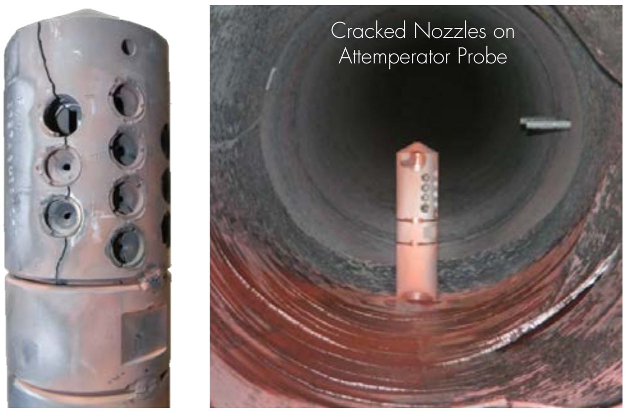
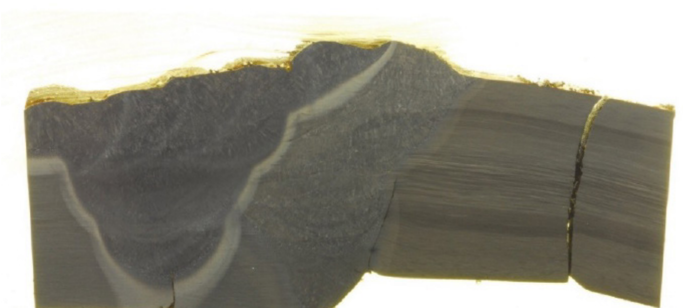


FIGURE 3. Python plot scripts that are generated and incorporated into PlantTrack™/SIIQ™.



Typical Attemperator Arrangement



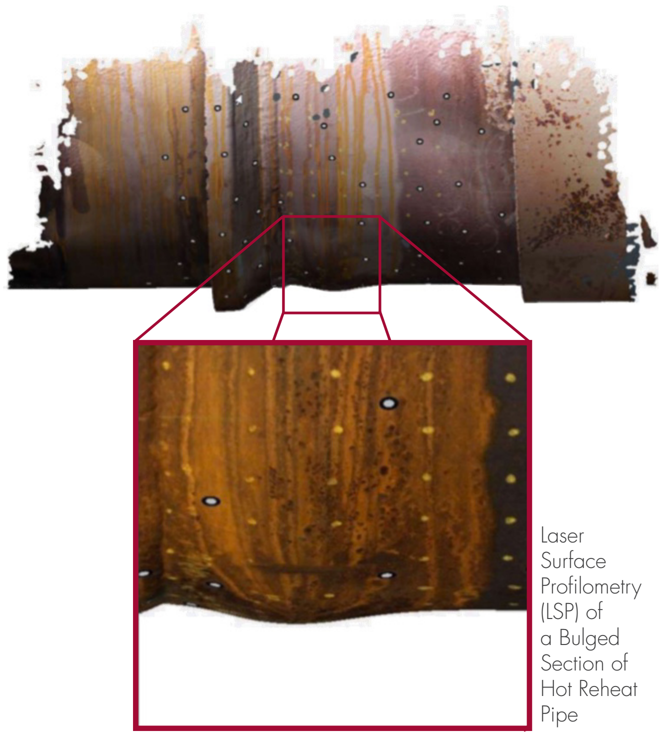


Metallurgical Cross-section of Girth Weld with Thermal Fatigue Damage

outage based on the damage accumulated. Like many combined cycle plants, attemperators are typically a problem area. Through monitoring, however, it can be determined when temperature differential events occur and to what magnitude. Armed with this information aides in root cause investigation but also, if no damage is recorded, may extend the inspection interval.

HRSG DAMAGE TRACKING

Many HRSG systems are susceptible to damage due to high temperatures and pressures as well as fluctuations and imbalances. Attemperators have been a leading cause of damage



Laser Surface Profilometry (LSP) of a Bulged Section of Hot Reheat Pipe

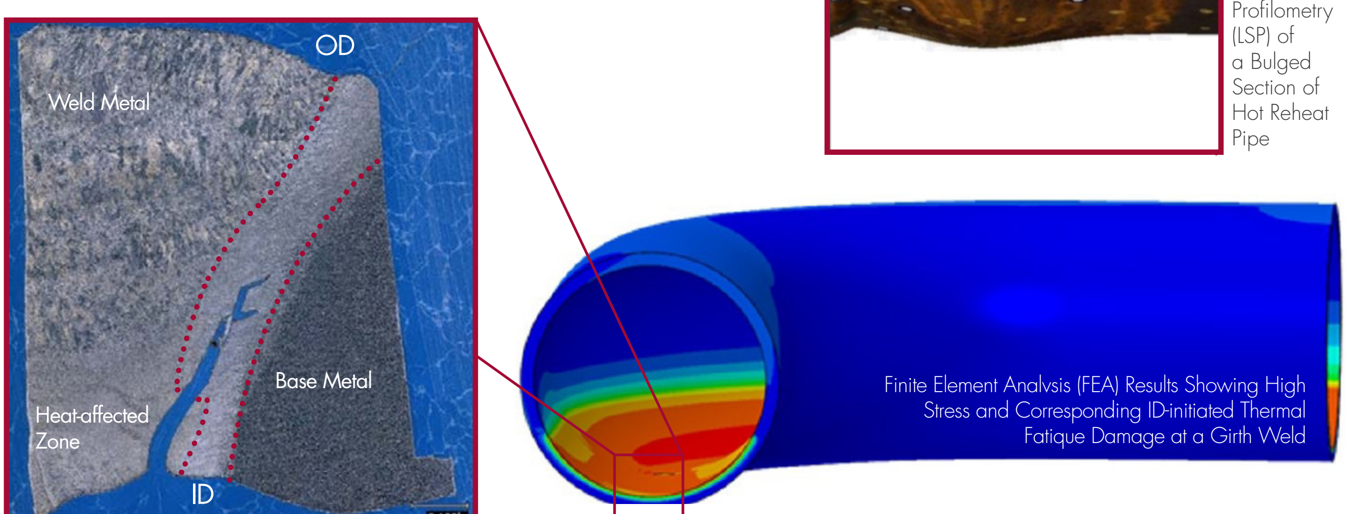
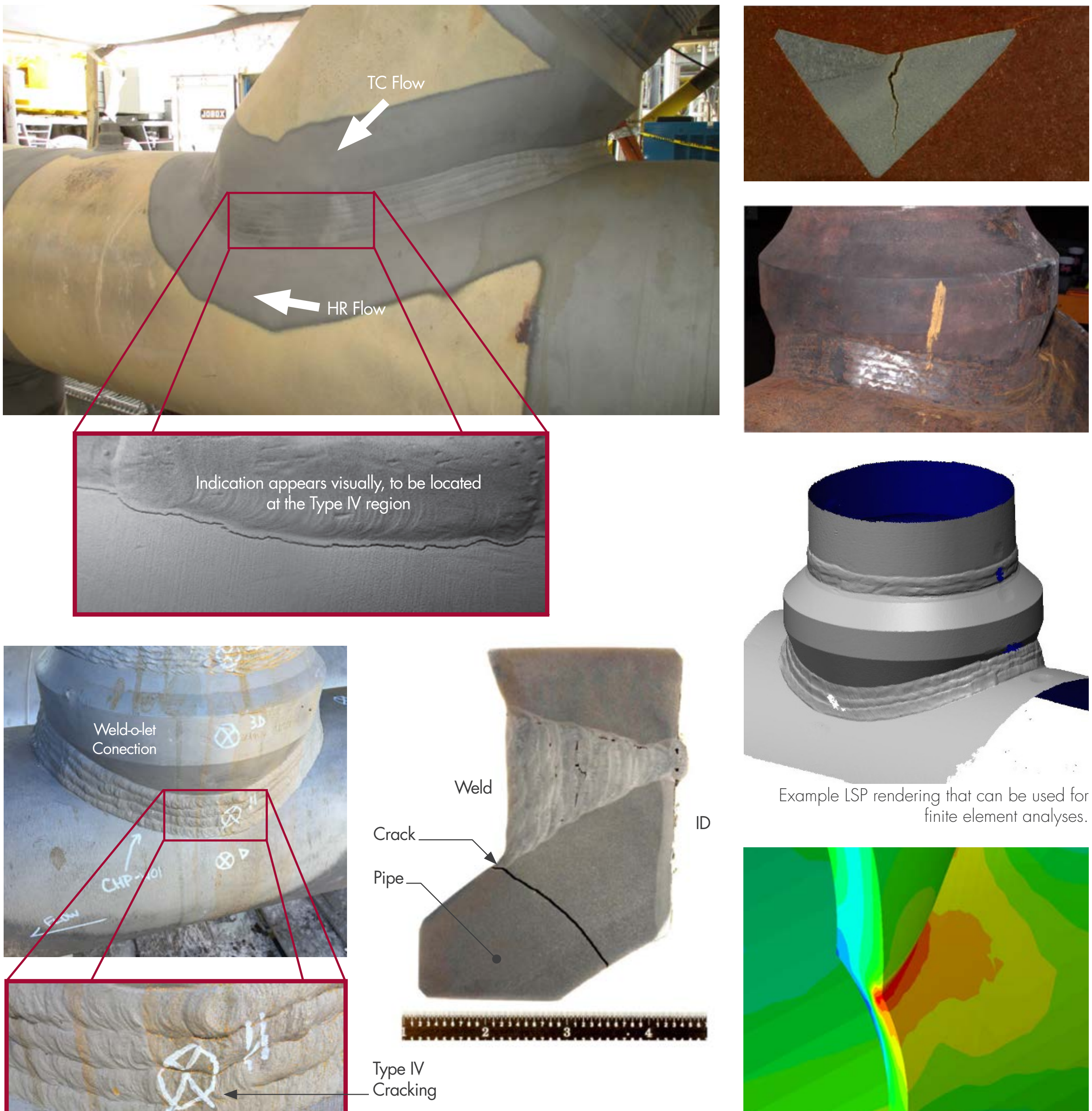


FIGURE 4. Examples of damage observed by SI on attemperators.

accumulation (fatigue) through improper design/operation of the spray water stations (Figure 5). In addition, periods of steady operation can result in accumulation of creep damage in header components (Figure 6) and unit cycling increases fatigue and creep-fatigue damage in stub/ terminal tubes and header ligaments (Figure 7). Monitoring the damage allows equipment owners to be proactive in mitigating or avoiding further damage.

Traditionally, periodic nondestructive examinations (NDE) would be used to determine the extent of damage, but in HRSGs this can be challenging due to access restraints and, in the case of the creep strength enhanced ferritic (CSEF) materials such as Grade 91, damage detection sensitivity is somewhat limited until near end of life. Continuous online monitoring and calculations of damage based on unit-specific finite element (FE) models (sometimes referred to as a 'digital twin') with live data addresses this issue.



Example LSP rendering that can be used for finite element analyses.

FIGURE 5. Examples of creep damage observed by SI on header link pipe connections (olets).

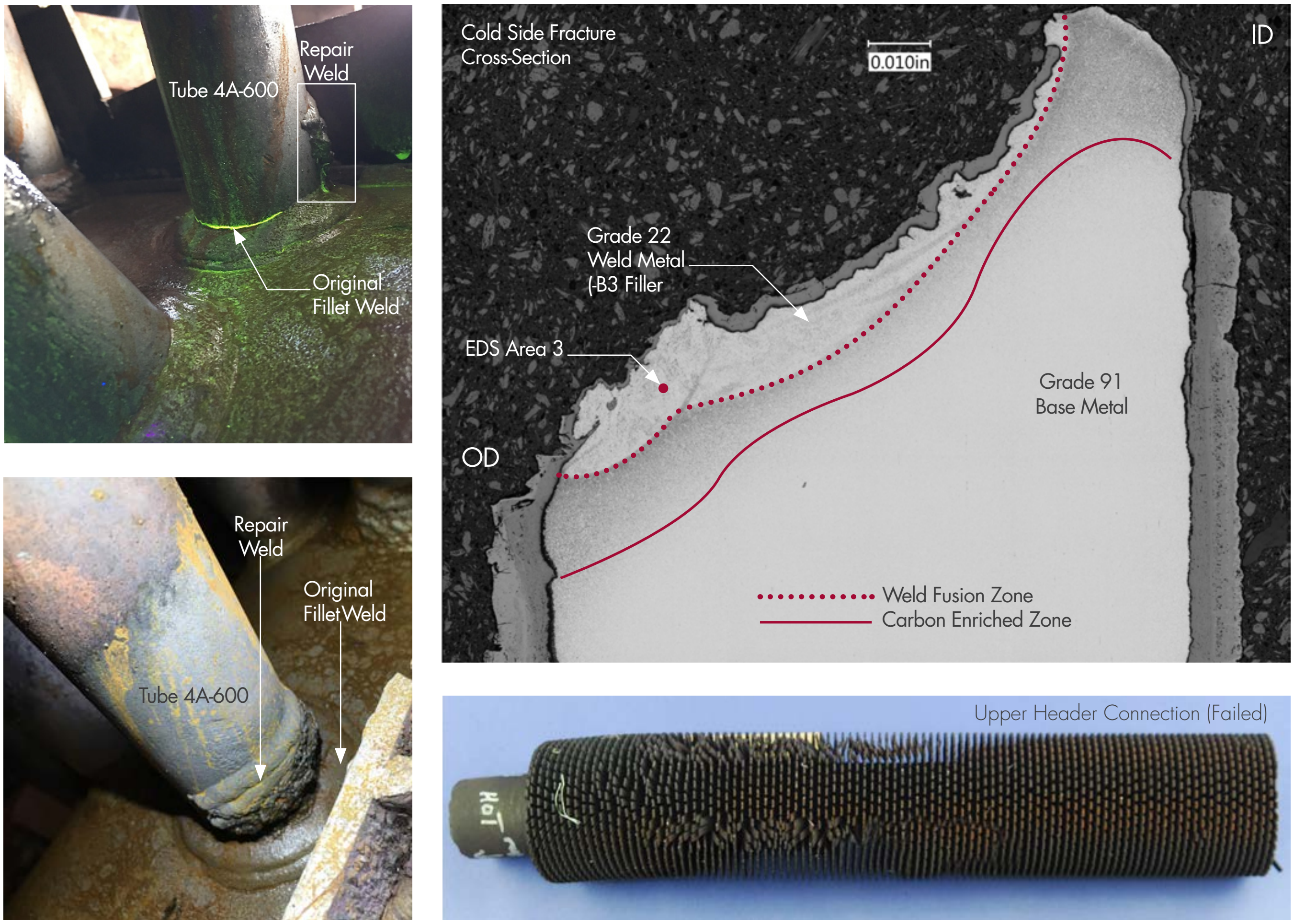


FIGURE 6. Examples of creep/fatigue damage observed by SI at tube-to-header connections.

Reliable life consumption estimates are made by applying SI's algorithms for real-time creep and fatigue damage tracking, which use operating data, available information on material conditions, and actual component geometry.

SIIQ tracks trends in damage accumulation to intelligently guide life management decisions, such as the need for targeted inspections, or more detailed "off-line" analysis of anomalous conditions. This marks a quantum leap forward from decision making based on a schedule rather than on actual asset condition.

FIGURE 7. Examples of online monitoring alerts generated from SIIQ™.

SIIQ can be configured to provide email alerts (Figure 7) when certain absolute damage levels are reached, or when a certain damage accumulation over a defined time frame is exceeded. In this way, the system can run hands-off in the background, and notify maintenance personnel when action might be required.

Heat Exchanger Tube Sheet Reliability Analysis

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BACKGROUND

The hot section of a waste heat boiler, also known as the hot spent boiler, is an essential component in the regeneration of spent sulfuric acid in chemical plants that process sulfur. Due to the ever-increasing demand for sulfuric acid and other sulfur compounds, this is critical equipment as its operation results in sold-out production. As a result, these boilers need maximum uptime between scheduled maintenance outages; any unscheduled shutdowns to repair and/ or replace tubes and tube sheets directly translate into lost revenues for the plant. This article addresses the reliability issues of one such boiler located in a Louisiana chemical plant.

GOAL: Predict the minimum number of tubes to plug, minimize downtime and allow regular operation until the next planned maintenance.

The boiler being assessed was part of an arrangement (Figure 1), with two fire tube boilers in parallel with a common external steam drum. In the case of the single boiler assessed by SI, the tubes were experiencing periodic tube leaks as the boiler was approaching the end of service life where tube failure frequency increases.. As typical, there may be a single tube leak or several in the same proximity (Figure 2). Some proactive plugging has been applied based on historical performance (Figure 3(a)). In SI's experience, tubes adjacent to a plugged tube may fail a short time after the plug is installed as there is an undefined temperature/stress interaction.
In addition to tube leaks, general corrosion and tube sheet thinning can be a consequence of tube leaks (Figure 2(c). Excessive tube sheet thinning is not uncommon due to the formation of sulfuric acid that exacerbates the corrosion issue. With these consequences in mind, it is critical that the proper number of tubes be plugged to stop the costly cascade of failures.

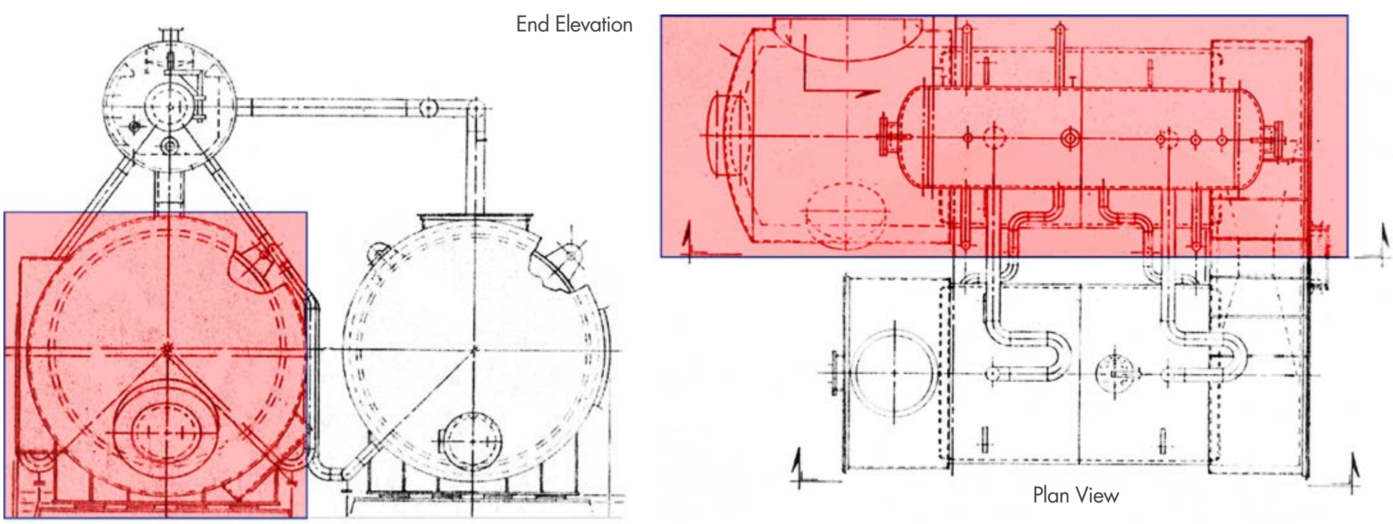
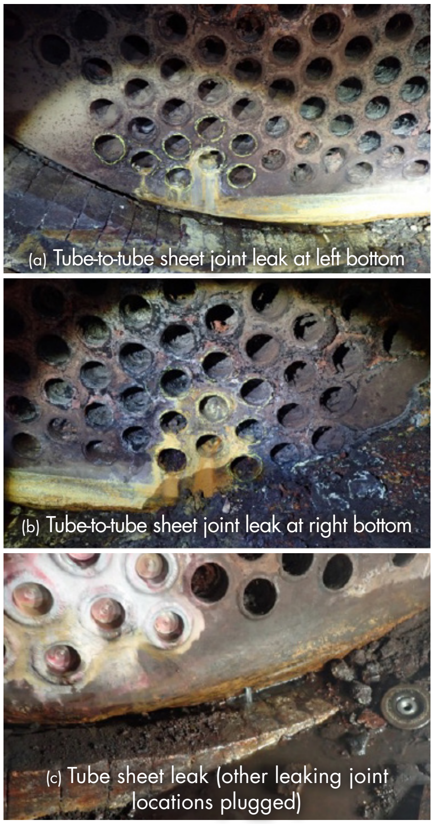


FIGURE 1. Hot Spent Boiler (shaded in red) in a waste heat recovery unit Flue Gas Tube Boiler.)



(a) Tube-to-tube sheet joint leak at left bottom

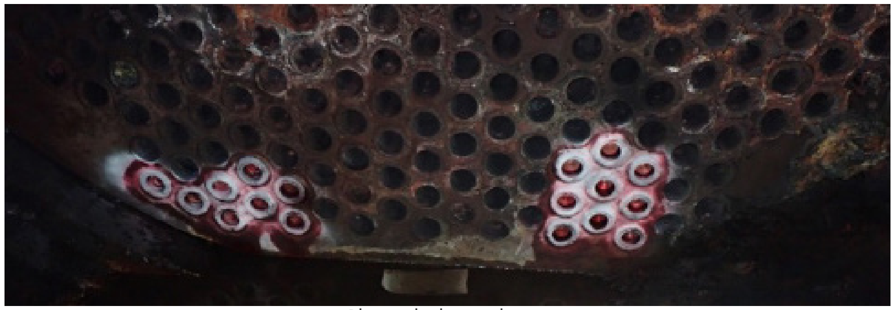
(b) Tube-to-tube sheet joint leak at right bottom

(c) Tube sheet leak (other leaking joint locations plugged)

FIGURE 2. Tube-to-tube sheet joint failures and tube sheet leak

To bring the boiler back to service, in early January of 2022, the leaking tubes and a few other tubes around the leaking tubes were plugged. In addition, to repair the leaking location in the tube sheet knuckle region, welding followed by post-weld heat treatment was performed (Figure 3(b)). Within a few weeks after this repair, additional tube leaks were discovered and required plugging. Such frequent leaks and repairs result in production loss and unplanned expenses. To minimize those, SI was contracted to develop an engineering basis for tube plugging, which would be proactive for equipment reliability, but not produce over-plugging that affects the boiler heat duty. To achieve this, the engineering assessment should involve an advanced analytical study to understand the following:

- Tube leaks
- Effect of repair, PWHT, and additional plugging on adjacent unplugged tubes
- Effect of tube sheet metal loss on the integrity of the tube sheet



(a) Plugged tube-to-tube joints

(b) Tube sheet repair at the bottom leak location

FIGURE 3. Hot Spent Boiler Plugging and Repair Welding

This article covers both the historic details of the failures and subsequent repairs and provides a comparison of the failures documented on-site with the analytical results determined from the approach implemented by SI.

METHODOLOGY & CRITERIA

The overall approach adopted by SI:

- Develop finite element (FE) model to study design deficiencies, if any, using elastic analyses. That is, perform an elastic finite element analysis (FEA).
- Develop a criterion to study the tube-to-tube sheet integrity.
- Using the same FE model, perform elastic-plastic analyses to determine the effect of repair and PWHT.
  - This is to determine if any additional tubes should be plugged to reduce any adverse effects.
  - This is a sequentially coupled thermal-stress analysis.
- Calculate the minimum required thickness for the various sections of the waste heat boiler.

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Table 1 illustrates the criteria considered for the work described herein. Several stress magnitudes were considered, such as the tube material allowable stress, tube-to-tube sheet joint allowable stress, and the ratcheting limit. Typically, when elastic analyses are performed, ratcheting limits are helpful. However, this work did not utilize the ratcheting limit. The tube-to-tube sheet joint allowable stress and load are calculated using Section VIII, Div. 1, Nonmandatory Appendix A. The allowable stress and load are compared against the equivalent stresses and tube axial loads, respectively, from the FEA to determine the mechanical integrity of the tube-to-tube sheet location. However, since there exists a parallel damage mechanism (general corrosion), the yield strength of the tube is set as a limit to add conservatism.

Criterial Considered	Criteria Selected ?
Tube Material Allowable Stress	No
Max. Allowable Joint Stress	Yes
Max. Allowable Joint Load	Yes
Tube Yield Strength (S_y)	Yes
$2S_y$ – Ratcheting Limit	No

TABLE 1. Criteria Used in the Analyses

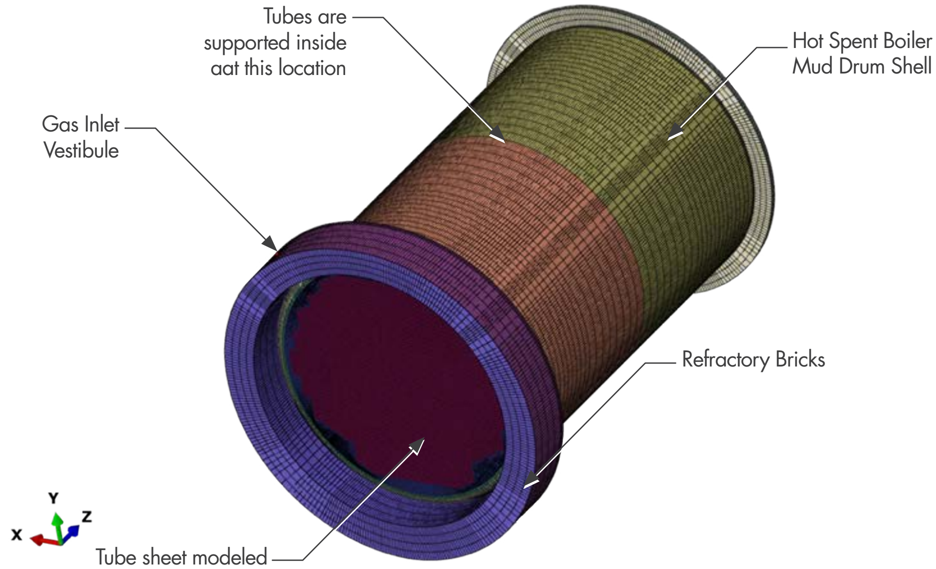

FIGURE 4. Hot Spent Boiler as Modeled in FEA

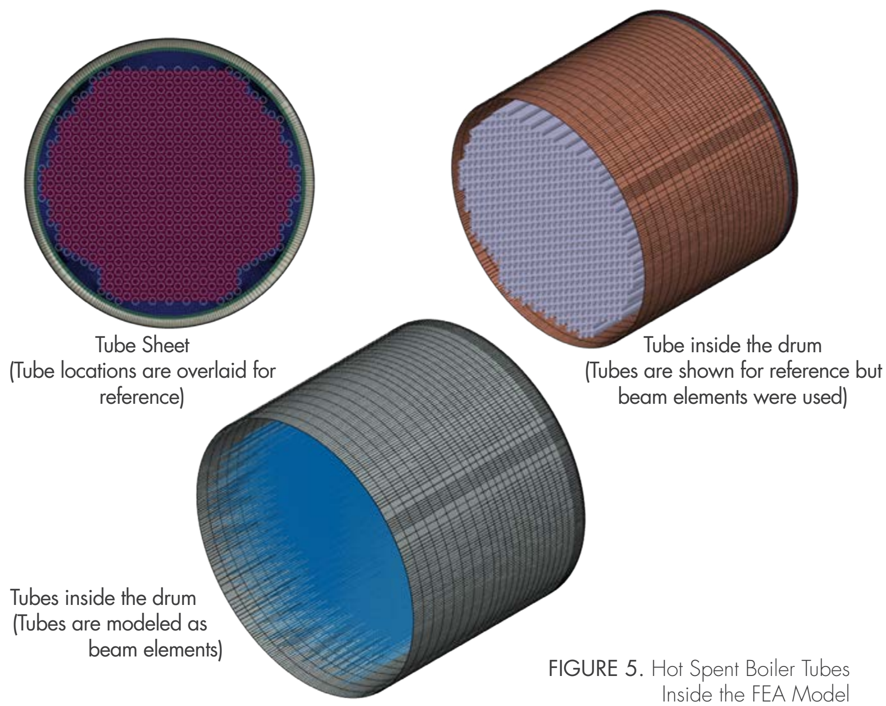

FIGURE 5. Hot Spent Boiler Tubes Inside the FEA Model

ANALYSES & RESULTS

Since the methodology requires the use of advanced analytical methods, an FEA model (Figure 4), was built and analyzed using the commercial FEA software package – Abaqus. The model included sufficient lengths of gas inlet and outlet sections ,the tube support location at the mid-section of the mud drum, the refractory, and the brackets that connect the hot section with the boiler drum. Since the nozzles are far from the area of interest, they are not included in the model. Appropriate element types were utilized for this work. One notable feature is the use of beam elements for the tubes (Figure 5). Since the model includes hundreds of tubes, incorporating a solid tube and heat exchanger model adds both geometric and numerical complexity. The use of beam elements simplifies the model while significantly minimizing the numerical convergence issues when compared with the full solid models.

All the analyses performed are thermo-mechanical analyses, wherein a heat transfer/thermal analysis is performed first, and the temperature profile from the thermal analysis is imposed along with respective mechanical loads in the subsequent stress/mechanical analysis. Initially, elastic models were used to assess the design adequacy of the subject boiler and to determine the bounding operating conditions for further analyses involving the repair process. For the analyses involving the weld repair and the post weld heat treatment (PWHT) followed by operating conditions, the sequence of steps is critical. SI discussed the methodology with the client when developing the accurate sequence to be included in the FEA. As stated earlier, to capture the effect of residual stresses (after welding and PWHT processes) on the corroded tube sheet section at the bottom where the leak was discovered, an elastic-plastic FEA is essential. Temperature results from the welding process step are shown in Figure 6. After welding and PWHT, the process conditions were applied to the model along with the number of plugged tubes at the time. Figure 7 illustrates the temperature distribution in the tube sheet, boiler drum, and tubes. Since the plugged tubes do not transport flue gas, the temperature of those tubes is the same as the water temperature around those tubes inside the drum.

Since the number of tubes is significant, post-processing of results is a challenge. SI developed a procedure to overlay the von Mises equivalent stress results on a spreadsheet layout that resembles the actual tube layout in the tube sheet. It is further simplified for better visualization in this article, as shown in Figures 8 through 10. Figure 10 (a) shows a historical perspective of the tube plugging over time. In the first set of analyses that SI performed, only the locations shown with greyish blue color (tubes plugged before Jan. 2022) were considered as plugged. The thermal analysis results for this case are shown in Figure 7. After performing the mechanical/stress analysis, it was observed that the unplugged tube locations shown in Figure 8 (a) with orange and red dots are of concern.

The orange dot locations indicate the locations with stresses greater than the tube yield strength. The red dot locations indicate that the stresses exceeded the allowable stress. Since the criteria are set at joint location stresses exceeding the tube allowable stresses, both orange and red dot locations require tube plugging. Figure 8 (b) shows the locations where further tube leaks were discovered within weeks of the weld repair and plugging. The tube leak locations are identified with yellow marks. This gives the confidence that such analytical methods, when appropriately applied, can predict the locations of future failures.

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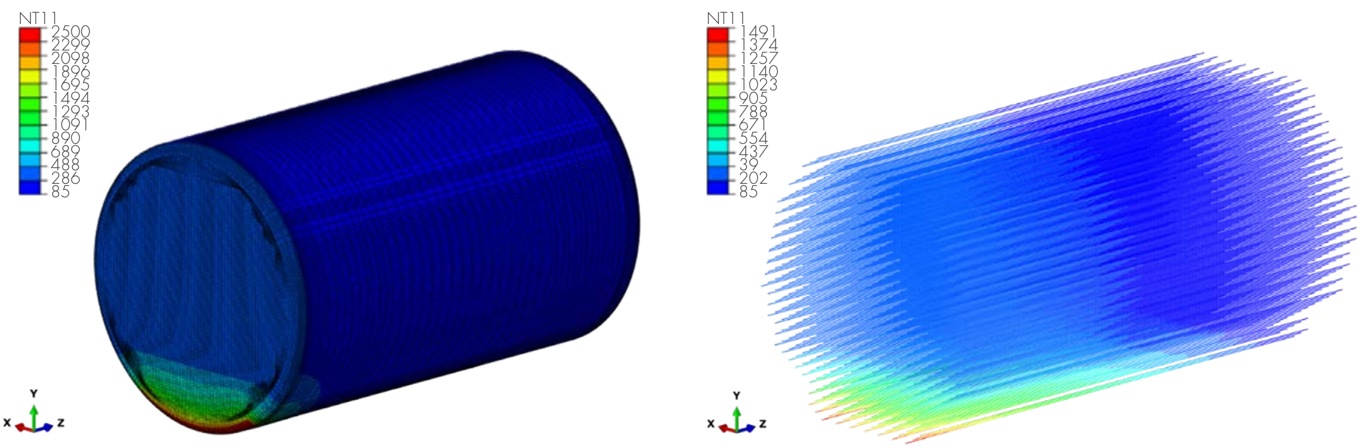


FIGURE 6. Repair Welding Simulation – Heat Transfer Analysis

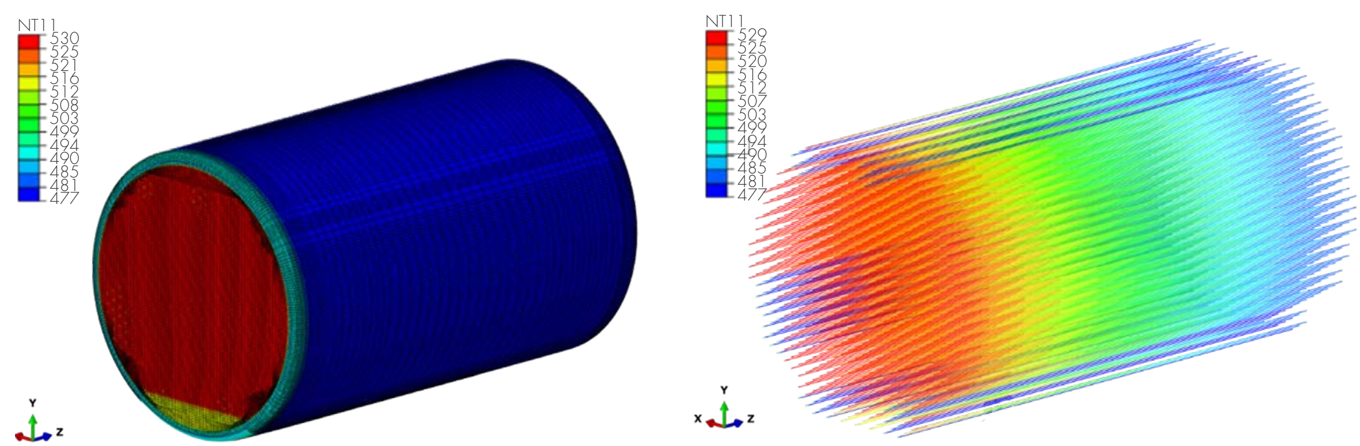
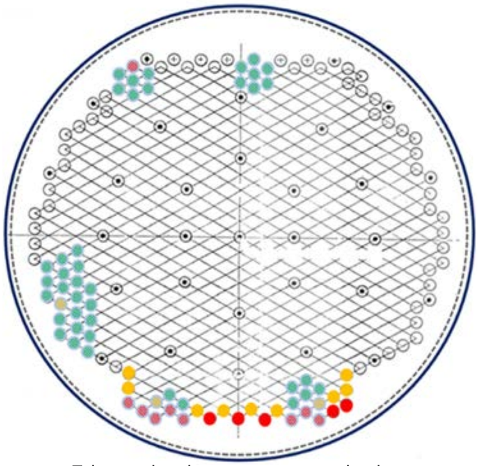


FIGURE 7. Post Repair and Plugging Process Conditions – Heat Transfer Analysis



(a) Tube-to-tube sheet joint criteria check

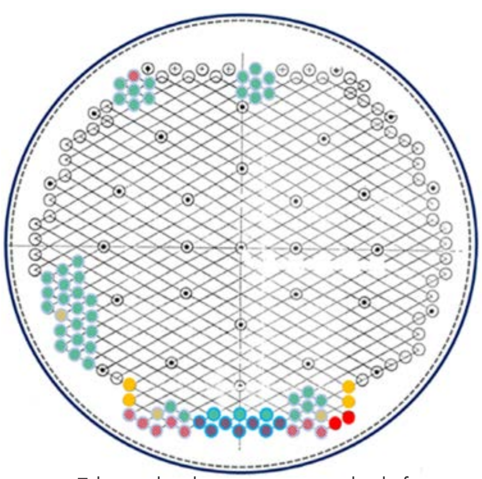
Legend
- Joint Stress > Yield
- Joint Stress > Joint Allowable
- Plugged Pre-Jan. 2022 with Joint Stress < Yield
- Plugged Pre-Jan. 2022 with Joint Stress > Joint Allowable
- Plugged Pre-Jan. 2022 with Joint Stress > Joint Allowable

(b) Tube-to-tube sheet joint leak at location of high stresses predicted by FEA

FIGURE 8. Post Repair and Plugging Process Conditions Criteria Check and Field Observation

After the discovery of the new leaks, further plugging was undertaken. These locations are identified by light blue dots in Figure 10 (a). SI incorporated these changes in the analyses and determined that the locations shown in red and orange dots in Figure 8 (a) are still a concern, as shown in Figure 9 (a). This was later confirmed by further tube leaks (see Figure 9 (b)) found after 6 weeks of the previous plugging was completed. This further assured the value of performing such an engineering-based approach rather than a traditional grand-fathering approach which would use plugging methods adapted for similar units based on historical information. It should be noted that SI was engaged in this study at the period between weld repair and second set of plugging as shown in Figure 8. However, all the results were made available just prior to the third leak shown in Figure 9 (b). At this time, the Client utilized the results from the FEA and decided to add additional tube plugging as shown in Figure 10. SI performed analyses with the final set of plugging, and the results indicated that other tube locations around the plugged tube locations are not of concern (see Figure 10 (b)).

The last set of analyses were performed in mid-March of 2022, and after 6 months, the boiler did not experience any further leaks. While the engineering approach predicted the issues, it is cautioned that any engineering analysis can only simulate the known degraded material thickness and properties in the analysis and not the corrosion degradation mechanism itself. The rate of deterioration and the interaction of various damage mechanisms should be monitored by the operator.

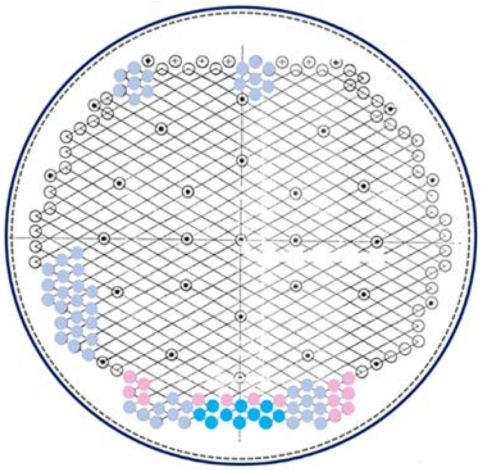


(a) Tube-to-tube sheet joint criteria checkafter additional plugging

(b) Tube-to-tube sheet joint leak at location of high stresses predicted by FEA

Legend
- Joint stress > Yield
- Joint Stress > Joint Allowable
- Plugged Pre-Jan. 2022 with Joint Stress < Yield
- Plugged Pre-Jan. 2022 with Joint Stress > Joint Allowable
- Plugged Pre-Jan. 2022 with Joint Stress > Joint Allowable
- Plugged Jan. 2022 with Joint Stress < Yield
- Plugged Jan. 2022 with Joint Stress > Yield
- Plugged Jan. 2022 with Joint Stress > Joint Allowable

FIGURE 9. Additional Plugging and Field Observation after that Plugging

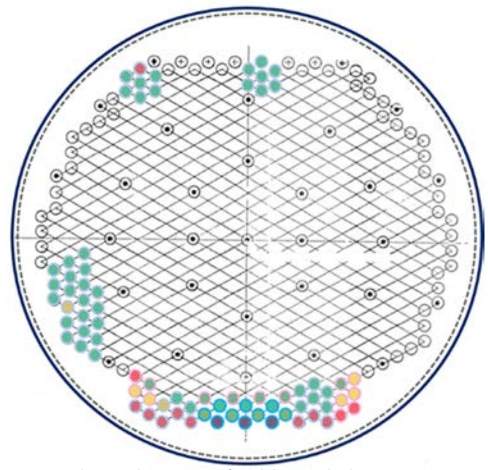


(a) Plugged Tubes - Chronological Display

- Tubes Plugged before Jan. 2022
- Tubes Plugged in Jan. 2022
- Tubes Plugged in Mar. 2022

Legend

- Plugged Pre-Jan. 2022 with Joint Stress < Yield
- Plugged Pre-Jan. 2022 with Joint Stress > Yield
- Plugged Pre-Jan. 2022 with Joint Stress > Joint Allowable
- Plugged Jan. 2022 with Joint Stress < Yield
- Plugged Jan. 2022 with Joint Stress > Yield
- Plugged Jan. 2022 with Joint Stress > Joint Allowable
- Plugged Mar. 2022 with Joint Stress < Yield
- Plugged Mar. 2022 with Joint Stress > Yield
- Plugged Mar. 2022 with Joint Stress > Joint Allowable



(b) Results - Adequacy of Additional Plugging

FIGURE 10. Tube plugging to-date and tube-to-tube sheet joint stress state

CONCLUSIONS

- The original, as-installed condition did not show significant issues. It is believed that other damage mechanisms caused the initial failures leading to the plugging of tubes around the periphery of the tube sheet.
- The study captured the recent joint issues, specifically the failure after the plugging and repair weld performed in early January 2022.
- Thinner regions are more prone to further failure. The minimum required thickness using the same criteria is established for the tube sheet.
- The analysis was successful in predicting the minimum number of tubes to plug.
- Plugging the correct number of tubes stopped the typical tube failure cascade.
- The applied results were directly proven. Once the results were fully implemented, the waste heat boiler had no unplanned shutdowns. The analysis met its goal and provided a major business impact.
- Analysts need sufficient information to minimize assumptions and make a robust model.
- Clear understanding of API 579, ASME Section VIII Div. 1, ASME Section I, and FEA is necessary to develop robust, realistic, and relevant engineering solutions.