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Structural Integrity Associates, Inc.®

NEWS & VIEWS

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INSPECTION OPTIMIZATION

CONDITION BASED MAINTENANCE SOLUTIONS FOR SAFE OPERATION

CEO Message

MARK W. MARANO | *President and CEO*
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Looking back at 2020 and as we move into 2021, it has been a time of significant change for all of us. Along with the challenges of the global pandemic, we have implemented significant changes at Structural Integrity. As the President/CEO of SI, a company I am honored to lead, I wanted to highlight the important changes over the past year from leadership, technology offerings, and our business health.

On the leadership side, we have added some key members to our Senior Team.

Tony Robinson joined SI in January 2021 as our new Chief Nuclear Officer and Senior Vice President of the Nuclear Business Unit.

Mike Battaglia joined SI as the Executive Director of Project Management Office/Nuclear Business Development Leader.

Steve Gressler was promoted to Vice President of the Fossil Business Unit.

On the product innovation solutions side, we are continuing on several fronts to address reliability and lower asset management cost in the following areas:

- Rapid Assessment of Boiler Tubes Using Guided Wave Testing (Fossil/NDE)
- Attemperator Monitoring with Wireless Sensors: Risk and Cost Reduction in Real Time (Fossil/NDE)
- The 4th Dimension: Lifecycle Assessment of Critical Structures (Critical Infrastructure)
- BG4 – BGMobile App: Know your System is Clean (Nuclear)
- PEGASUS©: An Advanced Analytical Tool for predicting and assessing nuclear fuel performance (Nuclear)
- Mission Critical Applications to Support the Mega-Rule (Oil & Gas)

Lastly, we continued growth of our critical assets, even amid the COVID environment, by hiring an additional 10% of new engineers/staff experts.

In the past year, I am pleased to share that SI has sustained the COVID pandemic challenges and is emerging in a much stronger financial position. This is the result of a significant improvement in expense control coupled with year-over-year orders growth. An added benefit of this performance, along with the aforementioned company changes, is that the morale of employees has measurably improved. A high-level summary of our recent employee survey, shown here, is evidence of this improvement.

I am confident this edition of News & Views will provide further insight into the things I have mentioned. SI will continue to be a premier provider to the industries we serve, and most importantly, we appreciate your confidence in our company. I look forward to the opportunity to see our clients again as we all emerge safely from the COVID environment.

2020 Employee Engagement Survey

Category	% Change	
Performance Management	8%	↑
Direct Supervision	8%	↑
Employee Enablement	3%	↑
Authority & Empowerment	3%	↑
Safety	2%	↑
Quality	9%	↑
Communication	13%	↑
Confidence in Leaders	32%	↑
Development	6%	↑
Work, Structure, Processes	15%	↑
Employee Engagement	6%	↑
Pay & Benefits	3%	↑
Respect & Recognition	5%	↑

Results from March 2020 to December 2020

In this Issue

SI Leadership | Our Senior Team

TONY ROBINSON
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Chief Nuclear Officer & Senior Vice President of the Nuclear Business Unit
Tony joined Structural Integrity with more than 30 years of progressive executive leadership in diverse areas of nuclear energy. He previously held various leadership roles with Framatome (formerly AREVA) as well as BWX Technologies. Tony brings to SI a wealth of technical and commercial leadership. His broad nuclear market knowledge includes expertise in formulating business strategy, cross-functional matrix leadership, employee development and retention, component, product and system engineering, and program / project management. Additionally, he has spent a considerable portion of his career in business development and complex commercial negotiations with clients as well as teaming partners. These leadership skills have given him the ability to work closely with customers, partners, and employees to ensure lasting and mutually beneficial relationships.

" I am excited to have the opportunity to work with and help lead the dedicated and highly skilled technical personnel at Structural Integrity who have a long history of bringing creative solutions to the nuclear market. These solutions have helped plant owners and other nuclear based organizations ensure the safe and reliable operation of their assets. In 2020, SI made some significant changes in leadership and business operations. These changes have positioned SI in much stronger organizational and financial health. I am confident that this renewed health is sustainable and will allow us to continue to support our clients as they extend the lives of their assets and/ or pursue new nuclear developments."

STEVE GRESSLER
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Vice President of the Fossil & Renewables Business Unit
Steve has innovated and led engineering and materials evaluations of power generation and district heating equipment for over 30 years. He is a principal contributor to life cycle programs, risk assessments, and evolving technologies that integrate sensors and analytics to enhance equipment serviceability predictions. Prior to his current role, Steve managed SI's Materials and Project Engineering groups and chaired our Nondestructive Testing Optimization council, which steers the development and deployment of our advanced nondestructive testing and sensor technologies. As Vice President, Steve oversees engineering, materials laboratories, and nondestructive testing services that help ensure the success of our fossil plant and renewable energy clients.

MIKE BATTAGLIA
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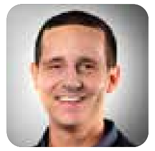
Executive Director, Project Management Office, Nuclear Business Development Leader
Mike comes to SI following tenures at Westinghouse Electric and Framatome. During his 25 year career in the nuclear industry, Mike has held a variety of leadership roles that spanned operations and business development. Selected accomplishments in the operations realm during that time included building and leading the Westinghouse Balance of Plant Engineering Department that included over 100 engineers, and leading the commercial deployment of a new alloy 600 mitigation technology in the US. From a commercial standpoint, Mike led the Business Development Departments for two different $75+m businesses to achieve substantial top-line growth.

Mike will bring a broad range of experience to SI to drive improvement in project management to achieve next-level performance and customer satisfaction. Mike will also hold a secondary role of Business Development in the SI Nuclear Business Unit, where he will use his experience and industry contacts to promote SI engineering technology to the global fleet.

Piping Fabricated Branch Connections



BEN RUCHTE
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Fabricated branch connections represent a common industry issue in combined cycle plants. Many are vulnerable to early damage development and have experienced failures. Despite these challenges, a well-engineered approach exists to ensure that the baseline condition is fully documented and a life management plan is put in place to help reduce the overall risk to personnel and to help improve plant reliability.

Fabricated branch connections between large bore pipes (including headers and manifolds) are often fabricated with a reinforced branch commonly in the form of a "catalogue" (standard size) fitting, such as an 'o-let'. These are more prevalent in today's combined cycle environment as compared to conventional units that used forged blocks or nozzles rather than welded-on, integrally reinforced pipe fittings. The fittings are typically thicker than the pipes in which they are installed to provide compensating reinforcement for the piping run penetration. Full reinforcement is often not achieved as the current Code requirements place all of the reinforcement on the branch side of the weld joint. As a result, higher sustained stresses are generated and, particularly in the case of creep strength enhanced ferritic (CSEF) steels, early formation creep cracking in the weld heat-affected zone (HAZ) can occur (known as Type IV damage – see Figure 1). The well documented challenges of incorrect heat treatment of the o-let weld can also add to the likelihood of damage in CSEF components. Damage is therefore most likely to occur in fabricated branches that operate with temperatures in the creep range.

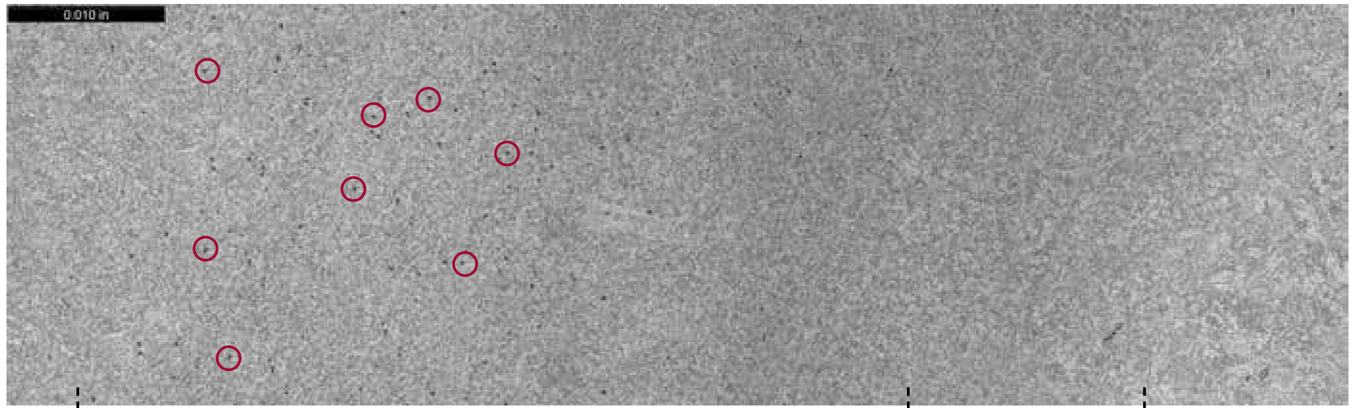

FIGURE 1. Examples of cavities located within the fine-grained HAZ (a few of the cavities are highlighted in red).

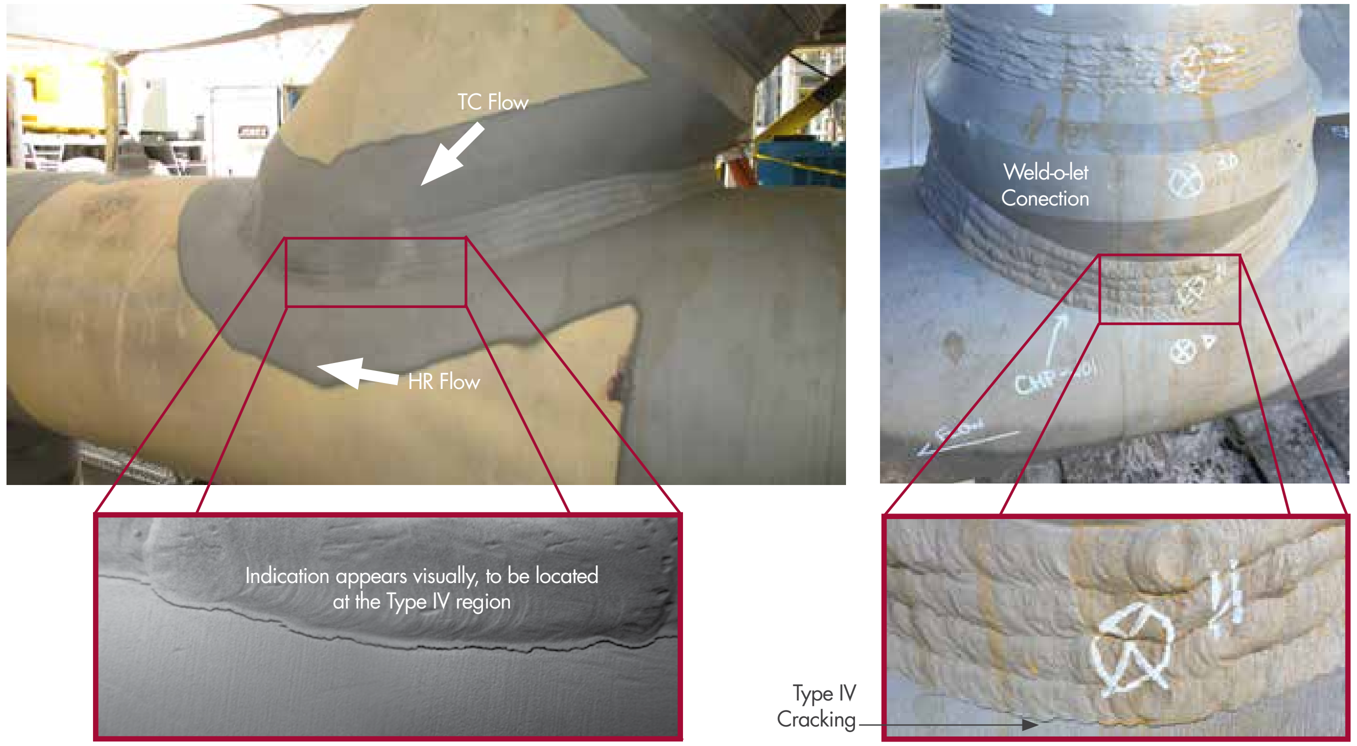

FIGURE 2. Example of cracking along the flank positions of o-let connections.

Damage is primarily in the form of creep cracking at the toe of the weld on the main run side of the connection (flank position), as shown in Figure 2. The susceptibility to damage early in life (in some cases, before 50,000 hours of service) has been widely reported. As early as 2008, a warning was issued by an architect engineering (AE) company to advise on the known problems. Despite that warning, use of these fittings with their associated inadequacies remains prevalent.

Several key factors contribute to early damage development for these components:

Temperature – Most combined cycle plants operate near the 1,040-1,050°F range, which increases the susceptibility to creep damage in Grade 91 HAZs. Some combined cycle plants operate at much lower temperatures (1,005-1,030°F), which can result in a marked increase in the cross-weld strength.

Geometry – Experience has shown that the size of the branch relative to the main run of piping can have a pronounced effect on the damage vulnerability. The larger the opening the more reinforcement that is needed at the weld joint. Current code requirements place all of the reinforcement on the branch side of the fitting. The amount of required integral reinforcement is defined only by consideration of the crotch location, not the flank location. This is a known limitation of the code which in many cases leaves the flank location with insufficient strength. Figure 3 shows an example of this with a cross-section through a weld-o-let where the small size of the weld compared to the thickest part of the nozzle fitting is evident. SI has performed detailed calculations of these types of cases and found that local stresses at the weld exceeded the allowable stress, even without consideration of weld strength reduction factors (WSRFs). The use of Grade 91 has highlighted this code deficiency both because of the weakness of the fine-grained HAZ in Grade 91 and because of its greater stress sensitivity (higher stress exponent) compared to common low-alloy steels.

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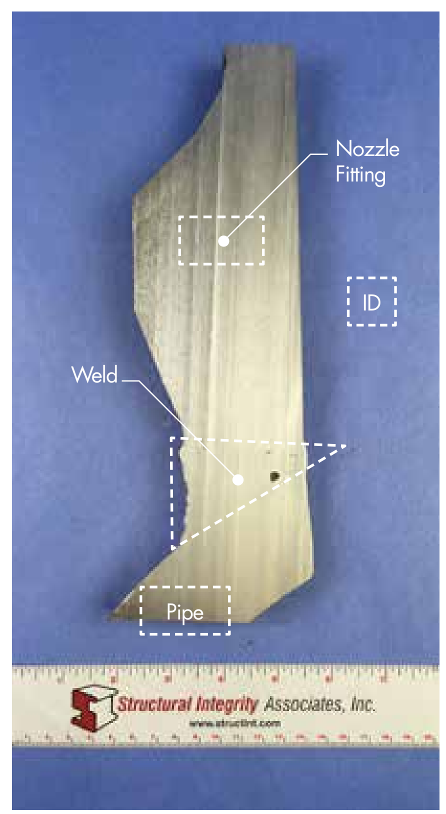

FIGURE 3. Example of a cross-section through a weld-o-let showing the small size of the weld compared to the thickest part of the nozzle fitting.

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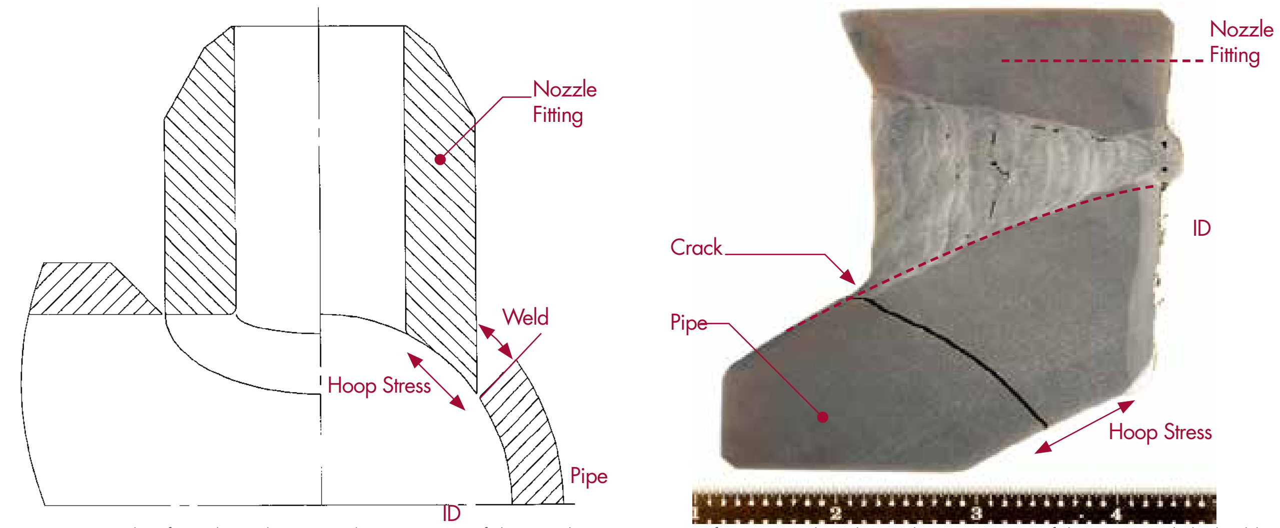

FIGURE 4. Example of 'set-through' LEFT and 'set-on' RIGHT fabricated connection configurations that shows the orientation of the HAZ (red dashed lines) compared to the hoop stress.

It is also important to mention the various styles of welded configurations (Figure 4):

- 'Set-on' represents a more standard o-let connection where the HAZ of the saddle weld follows the OD of the main run pipe and is oriented parallel to the internal hoop stress from pressure.
- 'Set-through' is less common and has mostly been associated with HRSG-supplied piping. In this configuration, the HAZ of the saddle weld traverses through the thickness of the main run pipe and is oriented mostly normal to the internal hoop stress from pressure.
  - This can result in much more rapid damage propagation.

Chemistry – As defined by EPRI, select impurity or tramp elements in high enough concentrations can reduce the damage tolerance of Grade 91 material resulting in greater cavitation susceptibility.

Added System Loads – Damage can become non-uniform and develop more rapidly across the flank positions when malfunctioning supports are in the vicinity of these connections (e.g. bending).

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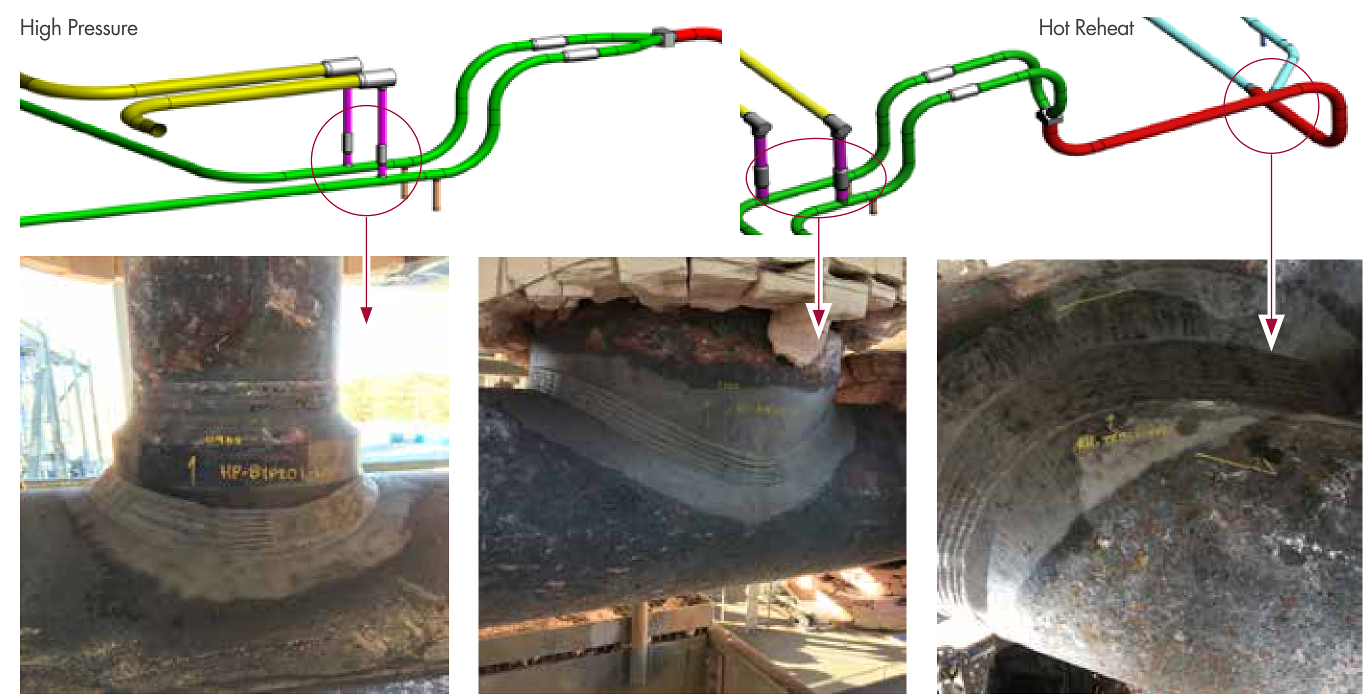

FIGURE 5. Example of common o-let locations within high energy piping (HEP) systems.

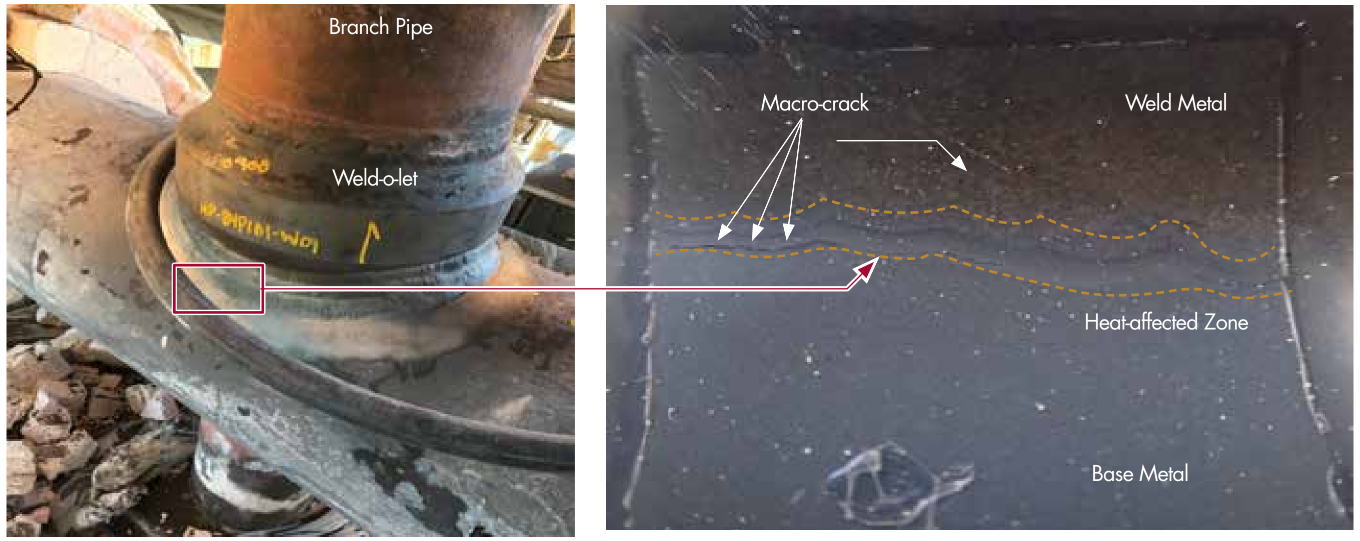

FIGURE 6. Example of a replication location at a flank position for a weld-o-let. A close-up of the replication site shows a macro-crack (red arrows) located within the Type IV zone (bound by the yellow lines).

Despite the numerous issues, there are several simple approaches to screen these connections:

1. Determine the piping systems that operate within the creep regime (typically high pressure/ main steam, hot reheat, gas turbine transition cooling, etc.).
2. Review detailed isometrics on both the architect engineering (AE), HRSG-supplied, and turbine-supplied piping looking for specific junctions (see Figure 5).
   a. Bypass take-offs
   b. HRSG-to-HRSG connection points
   c. Drains
   d. Turbine lead splits
   e. Link piping from HRSG-exit-to-collection manifolds
3. 'Golden ratio' of branch OD/ main run OD >0.5, where damage susceptibility increases as the ratio approaches 1 – SI has experience with damage development at ratios ≥0.5.
4. Verify materials of construction. The problem is intensified by the creep-weak nature of the Type IV location (fine-grained HAZ) in Grade 91 steel; however, low-alloy steels such as Grade 11 and Grade 22 are not immune.

If fabricated connections are identified, a baseline condition assessment through nondestructive examinations should be performed via several techniques:

1. Positive material identification (PMI) via X-ray fluorescence spectrometry (XRF) to assess general material compositions.
2. Ultrasonic wall thickness testing (UTT) to check thicknesses of the o-let, branch pipe, and main run pipe.
3. Wet fluorescent magnetic particle testing (WFMT) for identification of surface-connected defects.
4. Hardness testing of the surrounding area to detect possible anomalies from heat treating.
5. Metallurgical replication can be used to determine if creep cavities are present and should be performed at the main run pipe side toe at the flank locations on both sides of the connection (Figure 6).
6. Metal shavings can be collected from the main run of piping for a more detailed chemical analysis to determine if impurities or tramp elements are present at levels that could reduce the overall damage tolerance.
7. Laser surface profilometry (LSP) is a technique that can be used to capture a detailed 3D model of a component for an accurate geometry for computational modeling. While this technique does not provide any quantitative data itself, it is very useful in analytical techniques to determine potential geometric constraints that could result in additional sustained stresses on the component, which could significantly increase damage accumulation.

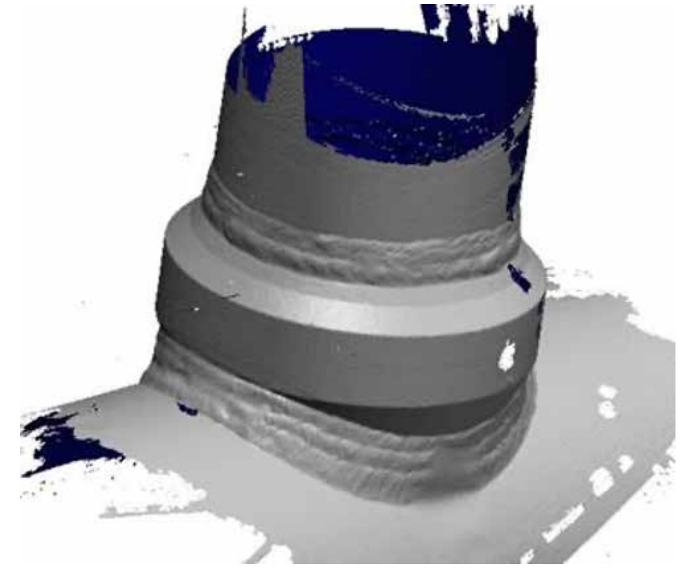

FIGURE 7. Example LSP rendering that can be used for finite element analyses.

FIGURE 8. Example of a fully contoured, uniform forging that can eliminate these problematic saddle weld joints.

Several steps can be considered to mitigate damage in these types of joints:

1. Weld build-up at the saddle, and in some cases the crown, can be applied to improve the strength of the connection. Finite element analysis, completed via the 3D model captured from the LSP scan (Figure 7), can be used to estimate the amount of weld build-up required to appropriately decrease stresses; however, the amount of weld buildup necessary is very often impractically large.

2. Replacing (or specifying) fabricated joints with forged fittings (Figure 8), which eliminates welding at the branch connection and provides a more balanced reinforcement, is the best method of dealing with these components.

3. Pipe support modifications to reduce bending and other system loads.

4. Re-normalizing and tempering the component after fabrication can minimize the detrimental effects of the HAZ and reduce the likelihood of Type IV cracking.

Summary

In summary, HEP systems should be globally reviewed to determine if these fabricated connections exist and to what level that they may pose a problem for safety and reliability of the plant. Once identified, a baseline condition assessment should be performed, and a life management plan should be implemented. Detailed engineering analyses that use models with the appropriate Grade 91 creep damage mechanics can be used to determine whether these components need true mitigation (repair/replacement) or if appropriate re-inspection intervals are a sufficient mitigation step. Consideration should also be given to assessing continuous operating data (temperatures and pressures) to help understand life consumption with actual operation.

Footnotes

[1] ASME B31.1 (requirements for integrally-reinforced branch fittings defined in Paragraph 127.4.8 and the associated Figure 127.4.8(E). Some requirements for the pressure design of such fittings are also provided in Paragraph 104.3.1 of ASME B31.1.

VOLUME 49 | **NEWS AND VIEWS** | FOSSIL & RENEWABLE POWER

Materials Lab Featured Damage Mechanism:

Soot Blower Erosion

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Soot blower erosion (SBE) is caused by mechanical removal of tube material due to the impingement on the tube wall of particles entrained in the "wet" blower steam. As the erosion becomes more severe, the tube wall thickness is reduced and eventually internal pressure causes the tube rupture.

FIGURE 1. View of a ruptured tube. The flat spots associated with severe wall loss are characteristic of SBE.

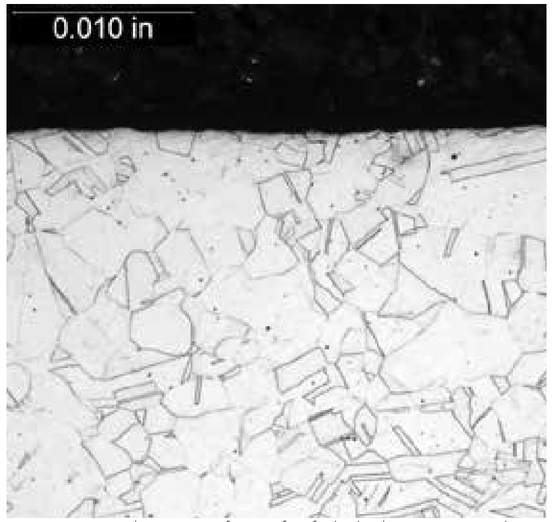

FIGURE 2. The OD surface of a failed tube section with a smooth surface indicative of erosion.

Mechanism

SBE is due to the loss of tube material caused by the impingement of ash particles entrained in the blowing steam on the tube OD surface. In addition to the direct loss of material by the mechanical erosion, SBE also removes the protective fireside oxide. (Where the erosion only affects the protective oxide layer on the fireside surface, the damage is more properly characterized as erosion-corrosion.) Due to the parabolic nature of the oxidation process, the fireside oxidation rate of the freshly exposed metal is increased. The rate of damage caused by the steam is related to the velocity and physical properties of the ash, the velocity of the particles and the approach or impact angle. While the damage sustained by the tube is a function of its resistance to erosion, its composition, and its operating temperature, the properties of the impinging particles are more influential in determining the rate of wall loss.

Typical Locations

Failures can occur anywhere soot blowers are located. For waterwall tubes, the damage will be located on the side of the tube facing the wall blower. Corner tubes and those near the lower slope may show damage over the entire circumference. Damage in superheater and reheater tubes usually occurs on the first tubes in from the wall entrance to the retractable blowers.

Features

- Severe OD wall loss
- Flat spots in areas of wall loss
- Lack of deposit/oxide in eroded areas

Root Causes

The primary cause for SBE has been linked to improper maintenance, including wet steam due to improper temperature settings or ineffective moisture traps as well as misaligned blowers. In addition, malfunctioning or "sticking" blowers, incorrectly set limit switches (particular to corner blowers), and improper head style can all contribute to SBE damage. Operational issues include excessive blower operation or blowing pressure, while an improperly located blower would be considered a design deficiency. The soot blower may operate automatically several times per shift, but if tubes do not have slag to blow off, the steam directly impinges onto the tubes.

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VOLUME 49 | **NEWS AND VIEWS** | FOSSIL & RENEWABLE POWER

Hydroelectric Penstock Inspection

Field NDE Services

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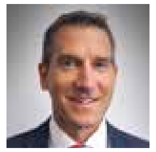

JEFF MILLIGAN
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Our talented experts, using the latest technology and methods, deliver unmatched value, actionable information, and engineering knowledge for the management of your most critical assets.

Many of the penstocks used in the hydroelectric power industry have been in service for over 50 years. Often with older components, historical documents like, as-built drawings and proof of material composition no longer exist. This information is critical for inspection, repair and replacement decisions. SI has the expertise to assist hydro clients with everything from material verification, inspection, and fitness-for-service analysis to keep penstock assets in-service for many more years to come.

MATERIAL VERIFICATION

Asset management of penstocks begins with understanding the material properties and composition of each component. SI has many tools to help determine material composition, including portable non-destructive products like positive material identification (PMI) x-ray fluorescent (XRF) analyzers and laser induced breakdown spectroscopy (LIBS) analyzers. These testing units have the ability to quickly and accurately measure percentages of key elements in metal materials. If a material sample can be removed from the component, by shavings, scoop, or boat sample, SI has a Material Science Center in Austin, TX, that utilizes a scanning electron microscope (SEM) with energy dispersive spectroscopy (EDS) capabilities to identify material elements. Material hardness is another piece of information that can be attained in the field with portable equipment to further help understand component characteristics like strength, ductility, and wear resistance.

INSPECTION

SI's talented experts, using the latest technology and methods, deliver unmatched value, actionable information, and engineering knowledge for the management of your most critical assets. We provide the following NDE services for our hydro customers:

- Corrosion mapping from internal or external surfaces
- Phased Array Ultrasonic Testing (PAUT) of welded joints
- PAUT of forge welds
- Short-Range Guided Wave Testing (SR-GWT) of riveted penstock lap-joints
- Rivet-head profiling and 3D laser scanning
- Inspection of anchor rods and studs

Corrosion mapping on external penstock surfaces is accomplished using a 3D laser scanner. A 3D scanning system provides an efficient and accurate way of performing external pipe corrosion mapping. This process is much quicker than the pit gauge method when setup time, inspection, data analysis, and reporting are considered. Positioning targets placed on the pipe prior to data acquisition allow the scanner to position itself without the use of any mechanical attachment. Since the targets are directly mounted to the pipe, data can be taken in vibrating environments. The analysis software generates on-site results that can

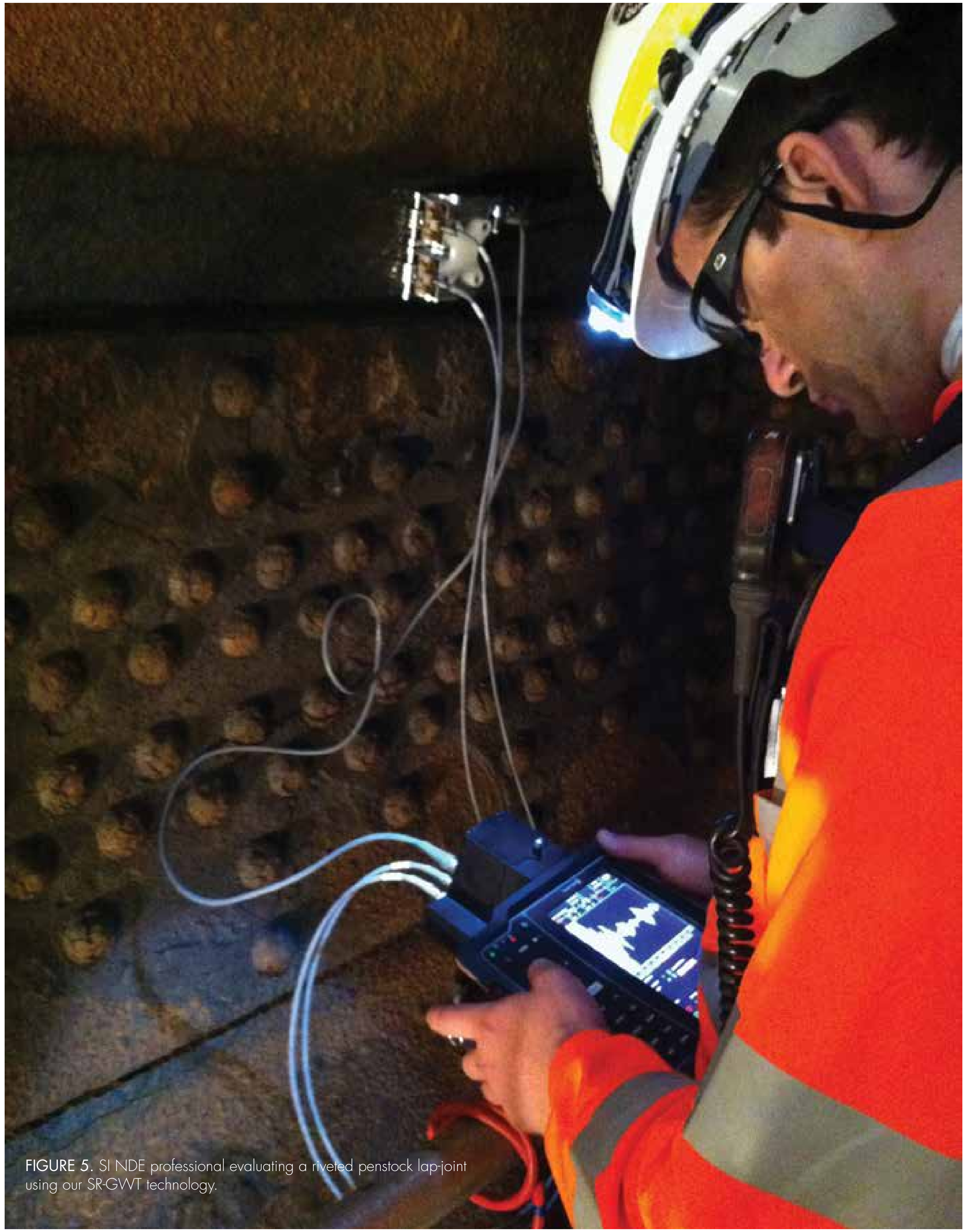

FIGURE 5. SI NDE professional evaluating a riveted penstock lap-joint using our SR-GWT technology.

quickly be exported to an Excel report displaying 3D color mapping, worst case profile, estimated burst pressure, river bottom path, and unwrapped 2D views. Burst pressure follows the methods based on ASME B31G code. The analysis software also has a pit gauge feature which formats the data similar to that of a conventional pit gauge. The 3D laser scanner has a resolution of 0.004 in. (0.1 mm) and an accuracy of 0.002 in. (0.05 mm) and can take 18,000 data points per second. The scanner is fully portable and can operate on battery power. Figure 1 shows a corroded pipe surface with positioning targets applied, along with the results of the laser scan highlighting minimum thickness locations.

For internal corrosion, an ultrasonic phased array corrosion probe can be manually encoded, or used with an automated scanner, from the external surface of penstocks to measure remaining wall thickness. The system is designed to inspect large areas quickly, efficiently, and accurately with high resolution encoded data. This process

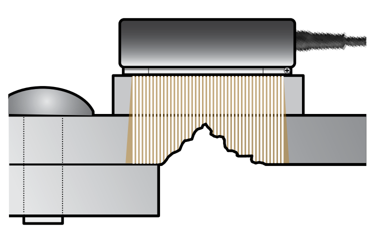

FIGURE 2. Image showing crevice corrosion and phased array corrosion probe beam coverage

has a resolution of approximately 1 mm x 1 mm spacing, enabling the collection of over 90,000 thickness readings per square foot. The phased array corrosion probe enables very sensitive near surface resolution to about 0.060 inches (1.5 mm) deep. Each probe pass covers a width of approximately 1.5 inches wide. These 1.5 inch wide encoded scan strips can be collected circumferentially or longitudinally along the penstock at scanning speeds up to 4 inches/second (100 mm/second). Figure 2 shows

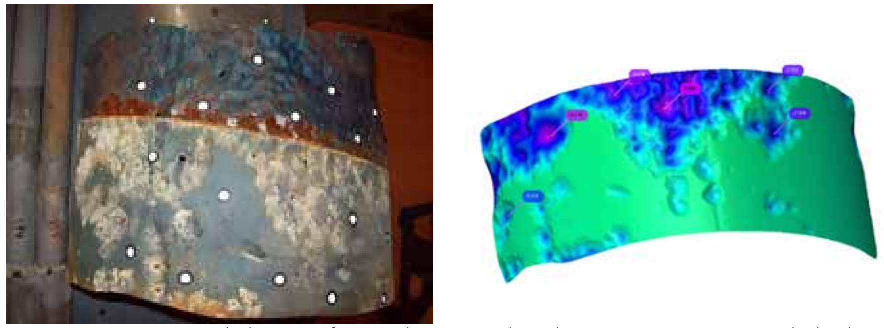

FIGURE 1. (a) Corroded pipe surface; (b) laser scan data showing corrosion spots with depths

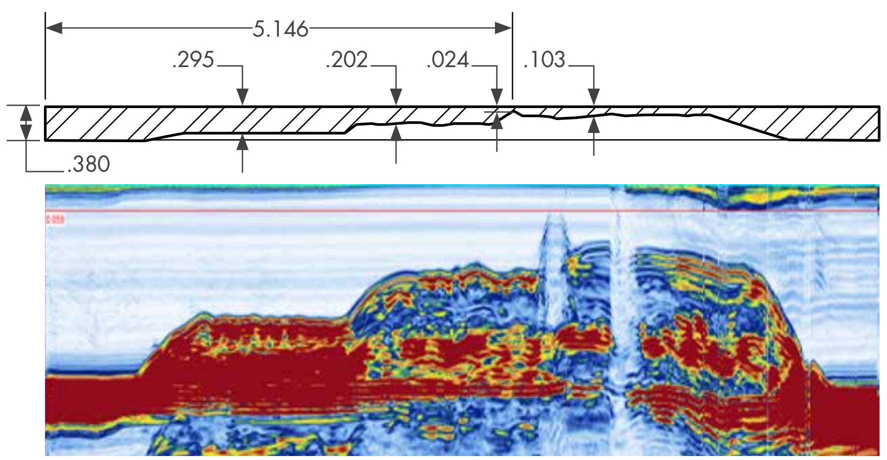

FIGURE 3. Drawing of corrosion calibration plate and phased array B-Scan display of corrosion calibration plate

the beam coverage of a phased array corrosion probe.

For this corrosion array scanning system, immediate analysis of the encoded strips of data via A-Scan, B-Scan, and C-Scan views is possible on-board the phased array ultrasonic inspection unit, thereby allowing the inspector the opportunity to identify areas of concern while still on the penstock. Figure 3 shows a phased array B-Scan display and drawing of a manufactured corrosion calibration plate. The individual scans (approximate 1.5 inches wide) can also be exported to off-line analysis software and merged together to show a complete C-Scan presentation of the inspection area, which uses a color coded scheme relative to material thickness. Figure 4 shows a PAUT C-Scan display of inspection data which represents a planar top-down view with the colors representing thickness values. Raw data thickness values recorded throughout the inspection area can also be exported using industry standard formats (e.g., CSV, Excel, etc.) to support further statistical analysis of the ultrasonic data.

One of the encoding devices used for internal corrosion inspection with the PAUT corrosion array probe was developed by SI and is known as the LATITUDE™ non-mechanized

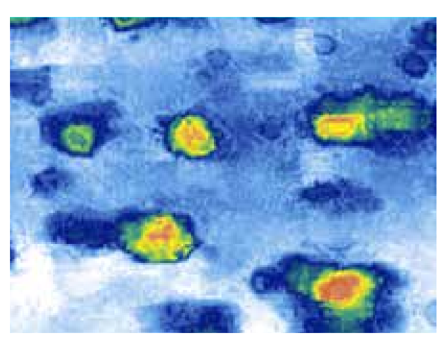

FIGURE 4. PAUT C-Scan display of corrosion data utilizing LATITUDE non-mechanized encoding technology

encoding system. Ultrasonic corrosion mapping services provided with LATITUDE eliminate the need for cumbersome automated inspection equipment, minimize the amount of post-processing time required, and provide high-resolution images of corroded penstock surfaces. A sample of the corrosion data recorded with LATITUDE can be seen in the C-Scan data illustrated in Figure 4.

Another unique NDE solution provided by SI includes the use of short-range guided wave testing (SR-GWT) to detect and characterize otherwise inaccessible crevice corrosion located behind butt-straps of riveted lap-joints. In this application, SI's SR-GWT technology uses sensors located adjacent to the edge of the butt-strap to generate ultrasonic guided waves that travel in the penstock shell, below the butt-strap, and reflect back from areas of volumetric wall loss. Figures 5-7 illustrate this application. For unique inspection challenges, SI has a team of NDE engineers that work directly with our clients to develop customized inspection solutions. This team has developed solutions for components/areas that were previously thought to be un-inspectable. These customized solutions have helped our clients verify the integrity of their assets, allowing them to operate with confidence and, in some cases, extend the serviceable life of critical components.

FIGURE 5. Photo of SR-GWT probe setup.

SI VALUE

SI provides comprehensive and integrated inspection and engineering services that enable optimized asset integrity management in the hydroelectric power industry. In addition to the services highlighted in the article, SI can provide risk ranking and management services to help identify critical assets and their susceptibilities; recommendations for targeted inspection strategies and methods; critical flaw size calculations; innovative inspection solutions delivered by NDE professionals; flaw evaluation and dispositioning; and the transformation of NDE data into actionable information that provides immediate value for the management of client assets.

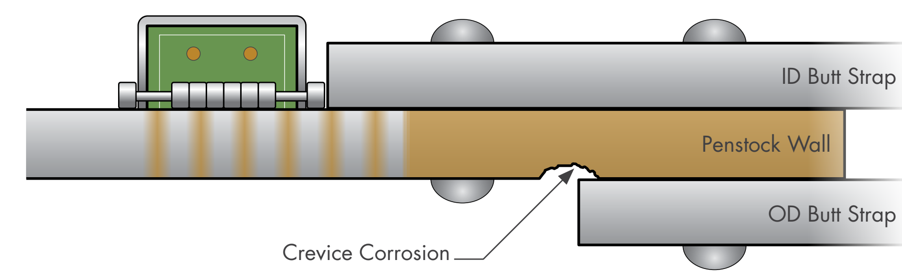

FIGURE 6. ABOVE Conceptual illustration showing the SR-GWT inspection of a riveted lap-joint for crevice corrosion.

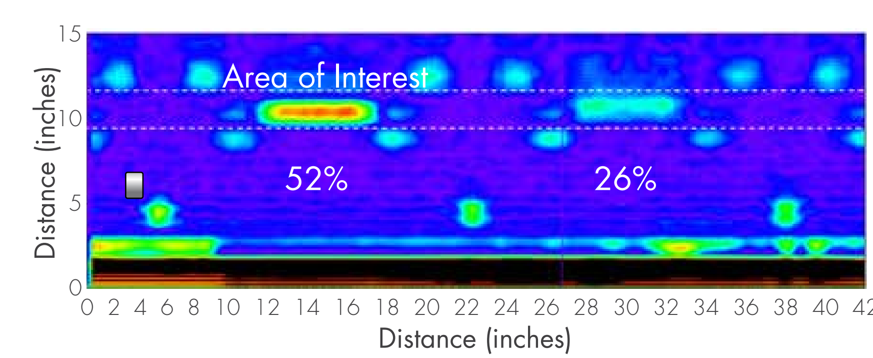

FIGURE 7. ABOVE SR-GWT inspection result showing the imaging of rivet holes and several calibration features (through-wall depths in white text) in a 1.25-inch thick plate; between white dotted lines is area of interest.

Attemperator Monitoring with Wireless Sensors

Risk and Cost Reduction in Real Time

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Installed sensors and continuous online monitoring are revolutionizing how power plants manage assets and risk by facilitating the transformation to condition-based maintenance routines. With access to near real-time data, condition assessments, and operating trends, operators have the opportunity to safely and intelligently reduce operations and maintenance costs and outage durations, maximize component lifecycles and uptime, and improve overall operating efficiency.

But not all data is created equal and determining what to monitor, where to monitor, selecting appropriate sensors, and determining data frequency are all critical decisions that impact data value. Furthermore, sensor procurement, installation services, data historian/storage, and data analysis are often provided by separate entities, which can lead to implementation challenges and disruptions to efficient data flow.

To provide our clients with a simplified implementation option that expedites the transition of data into intelligence, SI has developed a turnkey monitoring solution consisting of:

- Multipurpose wireless sensor network
- An independent data transmission infrastructure
- PlantTrack™ visual database integration
- Customizable automated alerts
- Automated engineering insight

While there are many applications in which effective monitoring can be used to more efficiently manage the operation and maintenance of passive assets, such as high energy piping, attemperator management is one specific application that clearly demonstrates the value that can come from an effective monitoring program.

Industry Issue

Attemperators (or desuperheaters), which reduce steam temperature using a water spray, are one of the most problematic components in combined cycle plants. There are several attemperator designs and configurations, but all are potentially vulnerable to damage. If the causes of damage are not addressed early, cracking and steam leaks can occur, leading to costly repairs and replacements. As is typically the case, currently installed data transmitters (pressure taps and thermowells) are located far downstream/upstream and cannot detect local transients that would suggest events like spraywater impingement, pooling, etc. The main challenge is that these events can lead to damage that often goes undetected until it is too late because the damaging temperature transients are not detected by standard plant control instrumentation. Without this local temperature data, it can be hard to predict when re-inspections/other mitigation steps should be pursued.

Monitoring Equipment/Capabilities

To better characterize local temperature events and provide early indication of non-optimal attemperator operating conditions, SI offers a combination of software and hardware components that can be implemented with a range of services from monitoring, detection to diagnostics. At the root of these services is the need to collect data from locally installed thermocouples (TCs). While some plants choose to run the signal through the data historian and then transmit to SI for processing, an alternative is to use our wireless sensor network to collect and transmit data. SI's wireless sensor network consists of two primary components: (1) a sensor node that collects the sensor data locally and transmits it wirelessly to (2) a gateway that transfers the data to the cloud. Figure 1 shows an image of SI's data collection node, highlighting several of its features. Each node has multiple sensor channels and is capable of collecting data from a variety of sensor types. For the case of temperature monitoring, up to nine different standard thermocouples can be connected to a single node.

FIGURE 1. Wireless data collection node.

FIGURE 5. SI's wireless node at the select combined cycle facility that has TC sensors connected.

Additionally, each node is battery powered and is available with an optional solar charging kit for outdoor installations. Furthermore, the data acquisitions nodes are weather-proof and designed to be installed in exposed locations.

As shown in Figure 2, the data acquisition node is installed locally and all thermocouples are hardwired to the node. The node then transmits the data wirelessly to the installed gateway using a proprietary 900MHz wireless protocol. The data collection and transmission frequency is adjustable based on the requirements of the application. The data from all installed nodes are transmitted to a locally installed wifi/cellular-enabled gateway, which stores the data on a local database until the data is successfully transmitted to a cloud database. Serving as the edge connection to the web, the gateway can be configured to use a cellular network, eliminating the need to connect to any plant networks, or it can be configured with a plant-wide wifi network, if available and accessible. The location of the gateway enclosure is flexible as long as it is within ~1000 ft of all installed data collection nodes.

PlantTrack App

Once transmitted off-site, data can be accessed through SI's PlantTrack platform. PlantTrack provides a suite of real-time event and damage tracking applications for common plant components: piping, headers, tubing, attemperators, etc. These applications interface to common DCS / Historian systems allowing for easy implementation, including review and analysis of historical data where that exists.

For attemperator damage, tracking of temperature differentials with strategically placed TCs provides a means to quantify the number and accumulation of thermal transient events. The signals from the TCs are analyzed to log temperature differential events exceeding some threshold, providing valuable data that can be used to target inspections and plan outage scopes more efficiently. Our software can be configured to provide email alerts when certain magnitude events occur or based on trends in temperature events. Optionally, if PlantTrack Online is connected to the site data historian, SI can fully implement the PlantTrack Attemperator Damage Tracking module, which uses additional sensor data to aid in diagnosing and trending attemperator damage. Actual diagnoses and recommended remediation involves one of SI's experts reviewing the data. This is made much easier with all the necessary data being compiled automatically within the PlantTrack system. Typical service includes reviewing the data on a periodic basis (e.g. quarterly) and providing a summary of damage events, likely causes, and recommended actions.

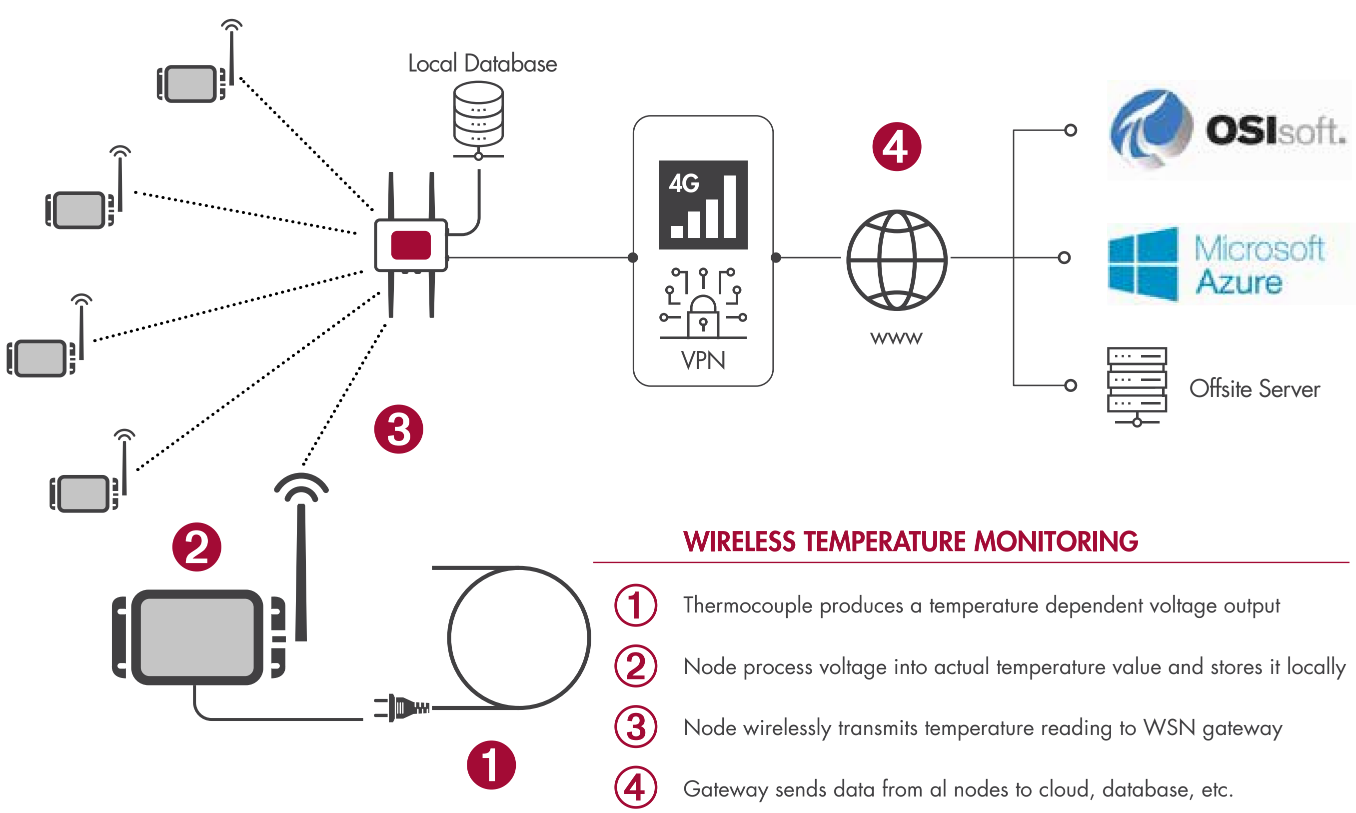

FIGURE 6. ABOVE Conceptual illustration showing the SR-GWT inspection of a riveted lap-joint for crevice corrosion.

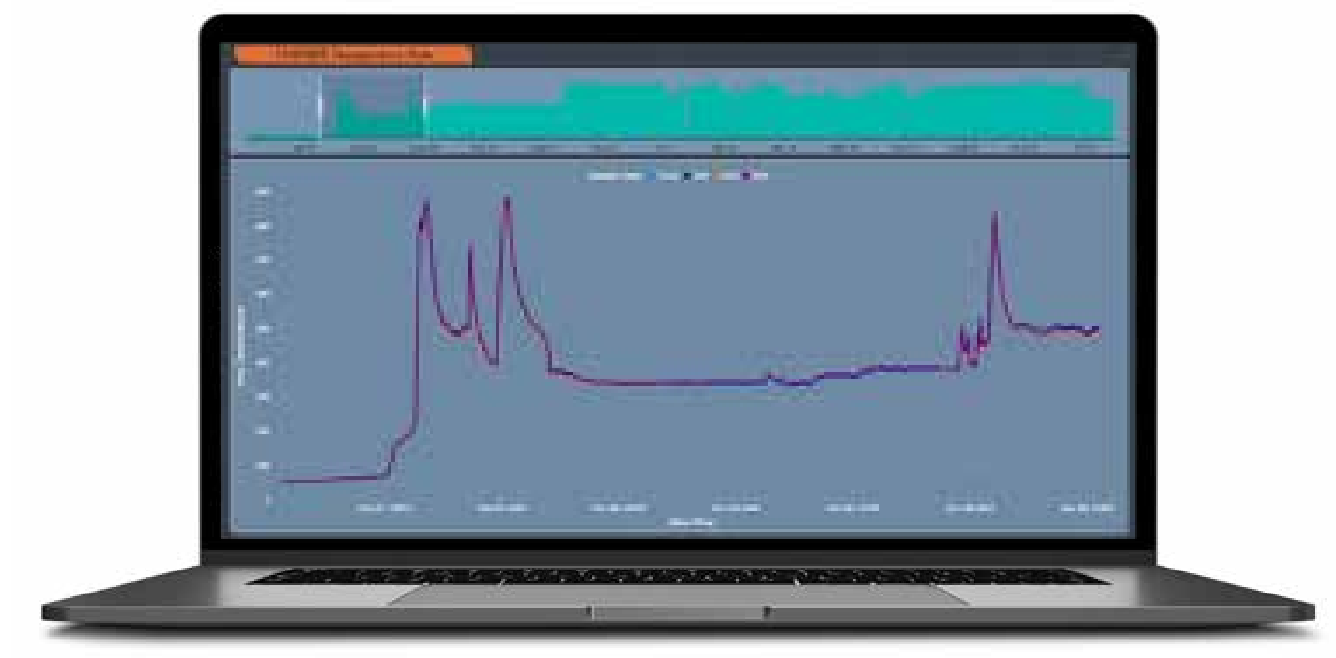

FIGURE 3. Thermocouple data display in PlantTrack.

FIGURE 4. Example automated email alert.

To provide some context, the following information provides two (2) case studies where continuous monitoring value was realized.

CASE 1: Bypass spray water stations (Maryland)

<u>Finding: Noted variances in warm-up line functionality and changes to the circumferential temperature differentials/upshock and downshock of the piping.</u>

A select combined cycle plant (2x1) recently experienced a through-wall leak at a girth weld on one of the HRSG's hot reheat to condenser bypass line. A ring section containing the failed girth weld was removed and submitted to SI's Materials Lab in Austin, Texas for review. The examination indicated that the crack was consistent with typical thermal fatigue damage, which is the expected damage mechanism for the area considering the proximity of a spray water station. SI recommended that the plant install local TCs to assess the magnitude of transients experienced during load change events and normal operation – the recommendation was made to instrument all four areas (2 hot reheat bypass, 2 high pressure bypass). SI also implemented our proprietary wireless sensor network where a node collects the TC data and transmits it wirelessly to a gateway that transfers the data to the cloud (Figure 5). Understanding the transients is the necessary first step, then evaluating/changing the logic, and follow-up with pertinent NDE inspections to ensure there is an understanding of the potential geometric factors here that could exacerbate any issue. If follow-on inspections find damage then the plant may also consider FEA/fracture mechanics to assess the timing of run/repair/replace options. It is also important to mention that the failed hot reheat bypass girth weld prompted the installation of a new spray water probe assembly to be completed at a later outage.

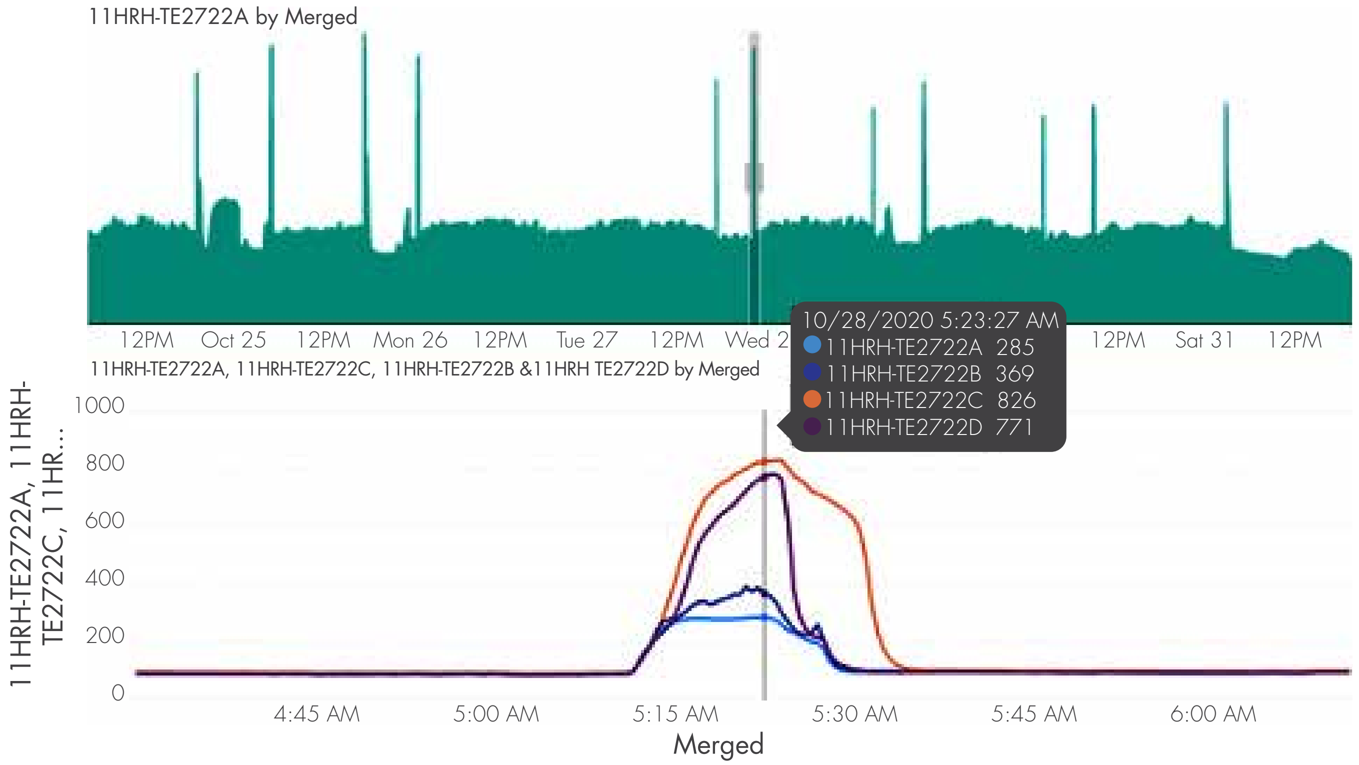

FIGURE 6. Pre-outage data for the hot reheat bypass system that experienced a failure.

SI performed a high-level review of the TC data pre- and post-installation of this new spray water probe assembly during a particular outage and also examined all of the bypass location temperature data:

- Pre-outage (data in Figure 6 shows 10/28/2020 @ ~5:20AM EST)
  - Warm-up line doesn't appear to be operational – data is similar to post-outage data for the other hot reheat bypass line (has not failed)
  - Several 'transient' periods show steady rates of temperature change
    - Sides of the pipe – ambient to ~750-850F and back down to ambient over 20-30 min period
    - Top/bottom – ambient to ~275-400F and back down to ambient over 20-30 min period
    - >400-500F differentials around the circumference
- Post-outage (data in Figure 7 shows 12/17/2020 @ ~10:50AM EST)
  - Warm-up line appears to be operational – now differs from the other HRSG hot reheat bypass (warm-up line appears to be malfunctioning/not in operation)
  - Several 'transient' periods show much more prominent upshock and downshock (~275F/min in the plot below)
  - Sides of the pipe – steady from ~700-750F
  - Top/bottom – steady from ~700-750F, but then experience differentials after prominent upshocks and downshocks before settling out
    - >250-300F differentials around the circumference
- Consensus on the pre- and post-outage data
  - Temperature differentials for the hot reheat bypass that failed appear to have improved from pre- to post-outage with a new probe assembly, but now with a functional warm-up line there are periods of more prominent temperature transients
    - Differentials around the circumference still exist
  - Spray nozzles can still be optimized

CASE 2: Reheat interstage spray water stations (Texas)

<u>Finding: Identified unevaporated spray water is present during cold starts and load changes. Resulting inspections identified prominent cracking of the piping in the vicinity of the spray water probe assembly.</u>

A select combined cycle plant (2x1) has a reheat interstage line that was previously identified by plant personnel as having a prominent sag with the low point located near the desuperheater in 2017. A liner was indicated on the drawing, which should protect pipe ID surface from spraywater. However, SI performed a high-level operating data review and performed localized NDE of this region (January 2018).

This initial data review considered existing transmitters (pressure, temperature, valve positions, combustion turbine loads, etc.) and found that there is some indication that the reheater desuperheater spray control valve is not fully closed, or may be leaking under some conditions. A leaking spray water valve could contribute to pipe bowing as that would make the bottom of the pipe colder than the top. Normally, if the desuperheater piping is able to flex, then when it is cold on the bottom and hot on the top it will hog (bow up). If, however, the piping flex is constrained so it cannot hog, then the pipe remains horizontal and a significant tensile stress is developed in the bottom of the pipe. This causes the pipe to effectively "stretch" on the bottom so the bottom is longer, and over time this can lead to a bow down. During the warm start there are a few minutes where the desuperheater pipe is at or below saturation temperature, which could result in condensation in that line. There could also be spray water that has collected in the line prior to startup that takes some time to evaporate. In either case the result would be a top to bottom temperature difference in the pipe.

From the inspection side there were no major issues noted, but a recommendation was made to install surface-mounted thermocouples (TCs) at pertinent locations to assess the magnitude of thermal transients experienced during load change events and normal operation. Plant personnel installed 5 TCs (2 upstream of the liner/2 downstream of the liner at the top and bottom of the piping; 1 at the extrados of the downstream bend). Plant personnel routed the TC sensors to their data historian (PI) for continuous monitoring.

SI was then requested to perform a review of this second dataset to determine if there are problematic temperature differentials within this line (October 2020). The data indicated that during the cold start and at low load operation (Figure 8 and Figure 9), the spray flow is not fully mixed and saturated steam is impinging on the top of the pipe downstream of the spray. This prompted another inspection (January 2021) now that saturated steam was identified and also prompted a review of the liner/probe assembly port.

This particular inspection identified circumferential indications consistent with ID-initiated thermal fatigue noted within liner boundary. This damage started at the downstream side of nozzle port and continued axially for ~5' before dissipating and was located from 10:00➔2:00 (top circumference). The through-wall depths were prominent – through-wall failure and several other locations with 40%+ (some rough measurements of

FIGURE 7. Post-outage data for the hot reheat bypass system that experienced a failure.

~60-80% through-wall noted, as well). It appeared that possible condensate may be inadvertently leaking around the nozzle assembly and entering the reheat interstage line through the nozzle port/flanged connection – once it hits a little bit of steam flow in the line it may push this into the void between the liner and ID of the pipe.

In areas that were originally slated for inspection (exit of the liner, downstream extrados of the bend), no findings were noted. The unevaporated spraywater that was identified by the secondary data review is obviously not ideal, but damage development is driven by the magnitude of the temperature transient and the cycle count and does not appear to have manifested in service damage at this stage. Continuous monitoring is advisable.

Summary

The crucial aspect in assessing the performance of these systems with spray water stations is being able to determine the magnitude and frequency of thermal transients. With the nearest temperature transmitters (thermoelements) typically located far downstream, local thermal transients at the conditioning valve and desuperheaters are often not detected. Surface-mounted thermocouples routed to the data historian/digital control system (DCS) or collected wirelessly help to evaluate temperature differentials around the pipe circumference and at geometrical impingement points. This, in conjunction with existing transmitters, allows for early detection of potentially damaging events so that appropriate mitigations (maintenance, logic updates, etc.) can be performed before costly repairs are required.

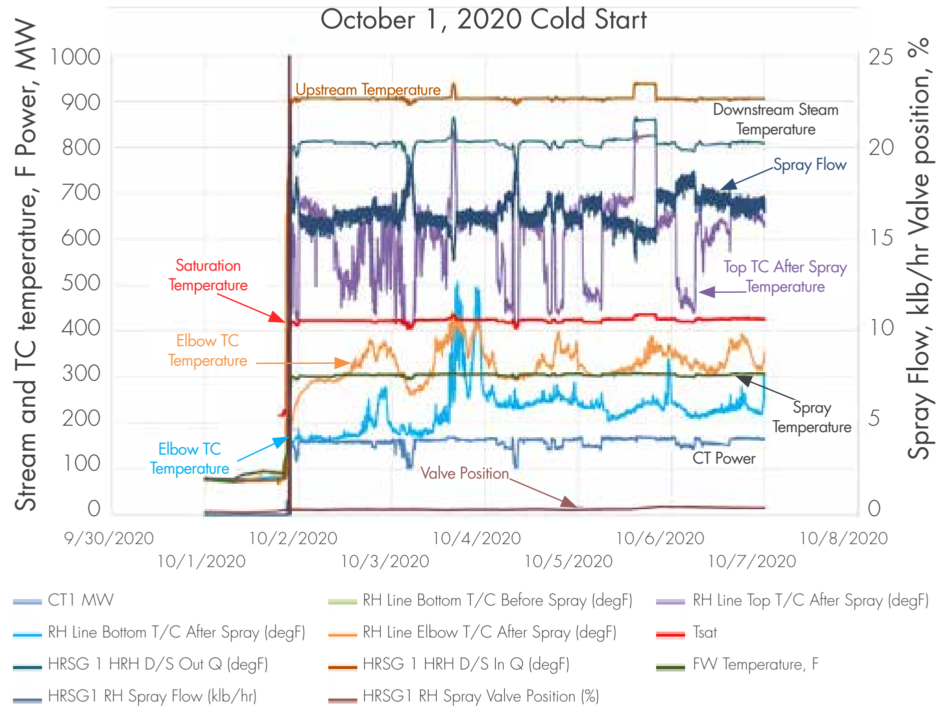

FIGURE 8. TC and existing transmitter data for a cold start that revealed unevaporated spray water in the reheat interstage line.

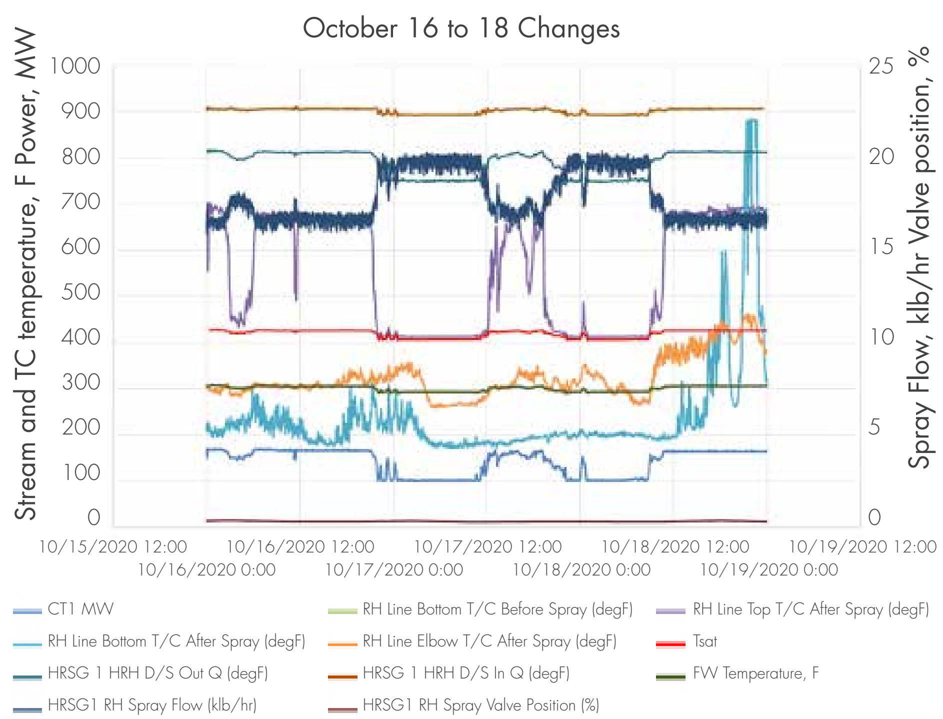

FIGURE 9. TC and existing transmitter data for a load change that revealed unevaporated spray water in the reheat interstage line.

Rapid Assessment of Boiler Tubes Using Guided Wave Testing

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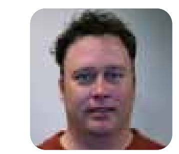

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Tubing in conventional boilers and heat-recovery steam generators (HRSGs) can be subject to various damage mechanisms. Under-deposit corrosion (UDC) mechanisms have wreaked havoc on conventional units for the past 40-50 years and have similarly worked their way into the more prevalent combined cycle facilities that employ HRSGs. Water chemistry, various operational transients, extended outage periods, etc. all play a detrimental role with regards to damage development (UDC, flow-accelerated corrosion, pitting, etc.).

An example of a horizontal section of boiler tubing that contained stagnant water during an extended outage, which resulted in pitting damage, can be seen in Figure 1. Identifying this type of damage with traditional ultrasonic thickness measurements can be time-consuming and unreliable given the large tightly packed tube population and highly localized nature of the damage encountered.

To address this issue, SI employs a guided wave testing (GWT) technique designed specifically for tube geometries that employs high-frequency ultrasonic guided waves and frequency tuning principles to optimize sensitivity to small diameter pitting. Advantages of SI's guided wave tube inspection methodology include:

FIGURE 1. Photographs of tube samples containing localized pitting caused by stagnant water and water chemistry issues.

GWT Tube Examination Advantages

- Quick, cost-effective inspection with 100% volumetric inspection of up to ~30 linear feet of tube from a single test location
- Broadband frequency tuning for optimized sensitivity to small diameter pitting across a range of tube geometries
- Low-profile sensor for fitting in densely packed tube configurations
- Minimizes the amount of surface preparation required for a comprehensive examination
- Provides a precise axial location and relative severity of identified indications for prioritizing follow-up activities
- Provides an efficient solution for assessing the extent of damage and identifying high-priority areas within a boiler

For more than a decade, SI has employed GWT for the rapid inspection of buried, insulated, or otherwise inaccessible piping in the nuclear, fossil, and oil & gas industries. The primary advantage of GWT is its ability to remotely detect and locate corrosion, providing reductions in both inspection time and cost. More recently, we have implemented a new GWT sensor that has been designed specifically for sensitivity to isolated pitting in small diameter tubing.

Figure 2 shows the configuration of the magnetostrictive GWT sensor that SI employs for tube inspections. It consists of a thin strip of highly magnetostrictive material, iron cobalt (FeCo), that contains a static biased magnetic field. A flexible current-carrying coil is then wrapped around the tube, over top of the FeCo. The flexible coil is pulsed with an alternating current wave packet that, in turn, induces a time-varying magnetic field around the current-carrying conductors. The interaction of the dynamic magnetic field generated by the coil and static magnetic field contained within the FeCo strip, result in small time-varying material displacements within the FeCo strip. When coupled to the external surface of a tube, these tiny oscillations transfer into the tube and continue to propagate along the length of the tube as ultrasonic guided waves, or guided stress waves. When the guided wave encounters a reflector, such as a weld, attachment, or corrosion, some of the energy is reflected back toward the sensor, where it is received and analyzed.

As seen in Figure 3, SI has successfully applied our GWT inspection technique for the rapid screening of reheater pendant tubes (boiler furnace) and economizer/superheater tubing (backpass). Figure 4 shows example GWT data from two different finishing superheater tubes:

Low-Profile magetostrictive GWT Tube Sensor

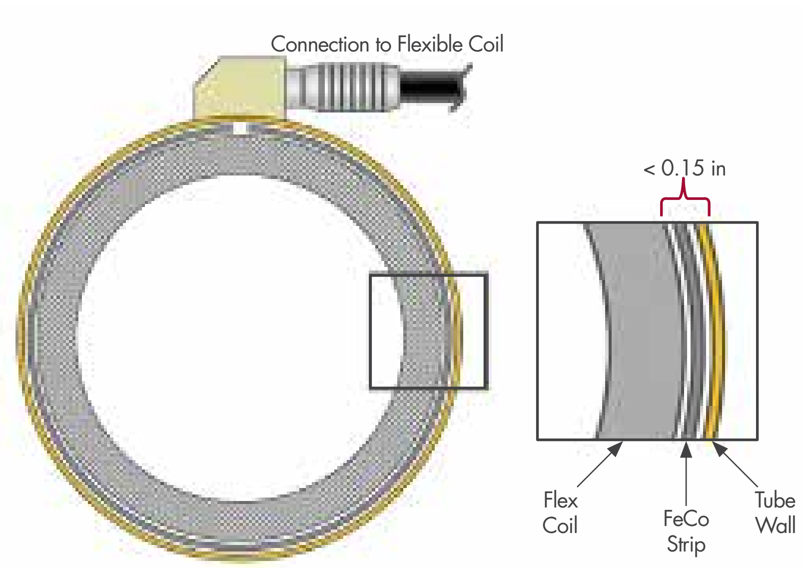

FIGURE 2. GWT tube inspection sensor configuration.

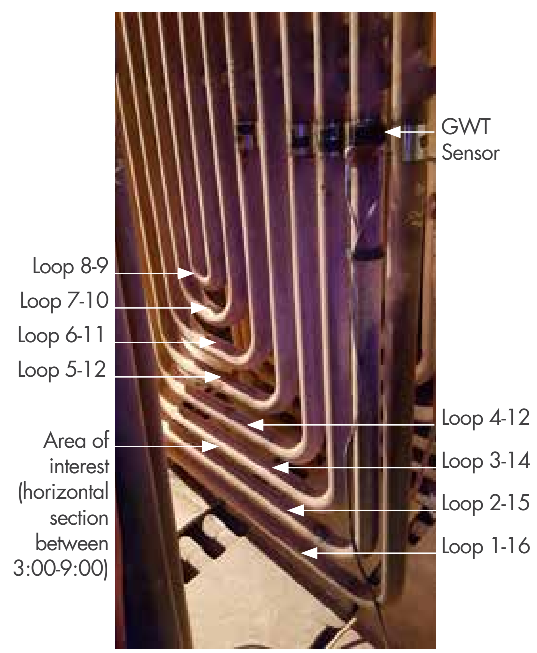

FIGURE 3. Photographs illustrating various applications in which GWT tube inspections can be beneficial.

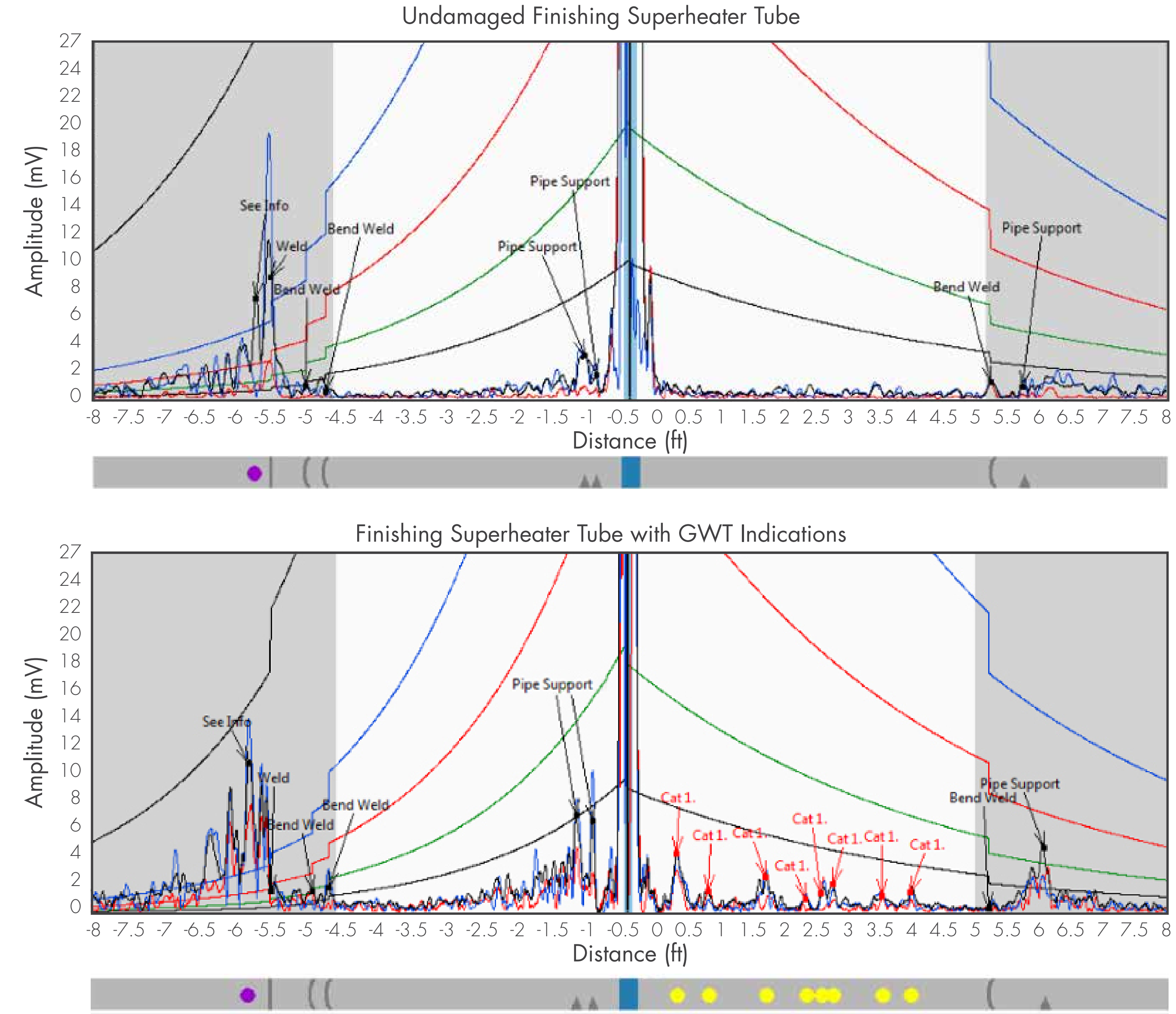

FIGURE 4. Example GWT data showing the examination results from an undamaged tube TOP and a tube with multiple GWT indications. BOTTOM

one clean tube (top) and one tube with multiple GWT indications (bottom). The indications in the bottom plot were confirmed to be localized small-diameter internal pits with up to 20% wall loss, illustrating the sensitivity of the technique.

When assessing boiler tubing for under-deposit corrosion, SI uses the described GWT technique to conduct a strategic sampling of tubes in various locations within a boiler to determine the high priority areas and diagnose the extent of pitting. When GWT indications are accessible, they are verified and depth-sized with UT, which helps to categorize the severity of GWT indications that are not accessible for direct examination. Depending on accessibility and tube geometry, we are typically able to conduct 100% volumetric examination of 150 to 200 linear feet of tubing per shift, significantly outpacing what can be accomplished with traditional ultrasonic thickness testing and other technologies that are only able to inspect a portion of the the tube circumference and require direct access to the inspection area.

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Inspection Optimization

Probabilistic Fracture Mechanics

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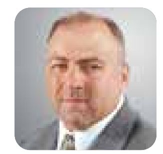
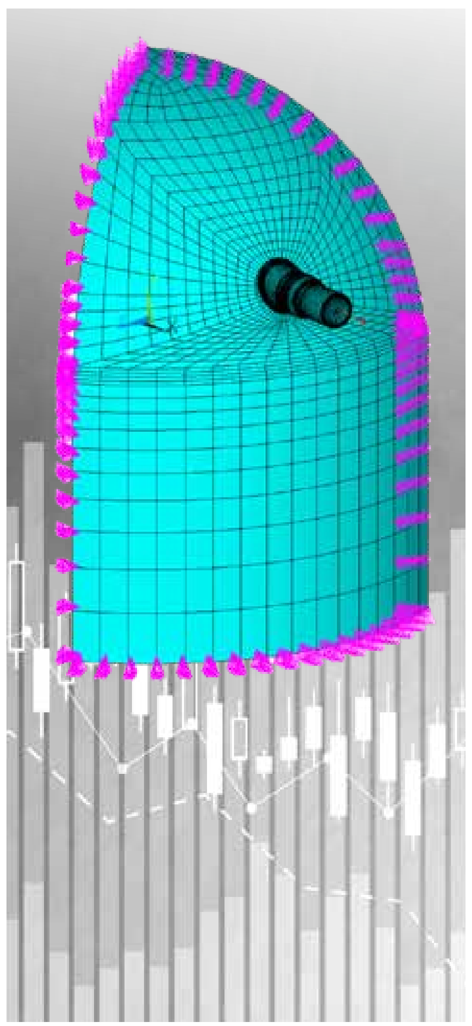




The goal was to determine whether the frequency of current inspection requirements was justified or could be optimized (i.e., increase the interval of certain inspections to devote more attention to higher-value inspections and thereby maximize overall plant safety).

Executive Summary

Welds and similar components in nuclear power plants are subjected to periodic examination under ASME Code, Section XI. Typically, examinations are performed during every ten-year inspection interval using volumetric examination techniques, or a combination of volumetric and surface examination techniques. Nuclear plants worldwide have performed numerous such inspections over plant history with few service induced flaws identified.

SI was selected by the Electric Power Research Institute (EPRI) to review the technical bases for the inspection intervals for select components. The goal was to determine whether the frequency of current inspection requirements was justified or could be optimized (i.e., increase the interval of certain inspections to devote more attention to higher-value inspections and thereby maximize overall plant safety.)

An inspection interval review takes into consideration industry operating experience (OE), operating history and previous inspection data. Many of the components / welds are difficult to access (require scaffolding and removing insulation), require manual techniques of inspection, and are typically in high radiological dose areas. The inspections can also have significant impact to outage duration. Reducing the frequency of inspections has the potential for time and cost savings during outages and reduces the radiation exposure to plant personnel. From the inspection interval review, one utility noted that increasing the inspection interval for steam generator nozzle welds from 10 years to 30 years would save over $600,000 of inspection and supporting activity costs over a 60-year licensed period of operation. Actual savings for a given plant are situation-dependent, although the potential for significant Operations and Maintenance (O&M) savings exists.

Background

To identify which components and inspection requirements were most suitable for optimization, EPRI performed an initial scoping investigation to collect the following information:

- The original bases for the examinations, if any;
- Applicable degradation mechanisms, and the potential to mitigate any potential damage associated with each mechanism;
- Operating experience, examination data, and examination results, e.g., fleet experience;
- Previous relief requests submitted to regulators;
- Industry guidance documents that replace or complement ASME Code requirements;
- Redundancy of inspections caused by other industry materials initiatives and activities (e.g., Boiling Water Reactor Vessel and Internals Project (BWRVIP), Materials Reliability Program (MRP), etc.); and
- Existing ASME Code Cases that provide alternatives to existing ASME Code inspection requirements and their bases.

After compilation and review of the information collected, EPRI and their members determined that the inspection requirements for the following components were among the most suitable for optimization:

- Pressurized water reactor (PWR) steam generator shell and nozzle welds and nozzle inside radius sections;
- PWR pressurizer shell and nozzle welds; and
- Boiling water reactor (BWR) heat exchanger shell and nozzle welds and nozzle inside radius sections.

Once the components were identified, EPRI contracted with SI to support development of the technical bases to optimize the related inspections. These evaluations are documented in the following four EPRI reports, all of which are publicly available for download at www.epri.com:

- Technical Bases for Inspection Requirements for PWR Steam Generator Feedwater and Main Steam Nozzle-to-Shell Welds and Nozzle Inside Radius Sections, EPRI, Palo Alto, CA: 2019. 3002014590.
- Technical Bases for Inspection Requirements for PWR Steam Generator Class 1 Nozzle-to-Vessel Welds and Class 2 Vessel Head, Shell, Tubesheet-to-Head, and Tubesheet-to-Shell Welds, EPRI, Palo Alto, CA: 2019. 3002015906.
- Technical Bases for Inspection Requirements for PWR Pressurizer Head, Shell-to-Head, and Nozzle-to-Vessel Welds, EPRI, Palo Alto, CA: 2019. 3002015905.
- Technical Bases for Examination Requirements for Class 2 BWR Heat Exchanger Nozzle-to-Shell Welds; Nozzle Inside Radius Sections; and Vessel Head, Shell, and Tubesheet-to-Shell Welds, EPRI, Palo Alto, CA: 2020. 3002018473.

Why It Matters

Recent efforts in the nuclear industry include a focus on reducing the cost of generating electricity to make nuclear more competitive with other sources (natural gas, etc.). A major component of these efforts is a targeted reduction of plant O&M costs, while ensuring that there is no detrimental impact on plant safety. Reducing low-value (i.e., low-risk, high-cost) inspections allows plant resources to be devoted to higher value activities (e.g., preventative maintenance). This is one benefit of employing risk-informed approaches.

The industry (in conjunction with EPRI, SI, and others) has shown a great deal of interest in employing risk-informed approaches where appropriate. Such efforts include (but are not limited to):

- Extremely Low Probability of Rupture (xLPR)
- ASME Code Case N-702 (alternative requirements for BWR nozzle inner radius and nozzle-to-shell welds)
- ASME Code Case N-711 (volume of primary interest)
- ASME Code Case N-716-1 (streamlined risk-informed inservice inspection)
- ASME Code Case N-752 (risk-informed repair / replacement)
- ASME Code Case N-770-6 (cold leg piping dissimilar metal butt weld inspection)
- ASME Code Case N-864 (reactor vessel threads in flange examinations)
- ASME Code Case N-885 (alternative requirements for interior of reactor vessel, welded core support structures and interior attachments to reactor vessels, and removable core support structures)
- ASME Code Case N-[xxx] (alternative requirements for pressure-retaining bolting greater than 2 inches in diameter)
- 10CFR50.69 (risk-informed categorization and treatment of systems, structures, and components)

The inspection optimization approach discussed here is congruent with these other approaches, as it uses probabilistic and risk insights to help plants to prioritize inspection and maintenance activities on those components most significant to plant safety.

Continued on next page

How It's Done

In the four EPRI reports cited above, the technical basis for increasing the interval of components inspections included the following steps:

- Review of previous related projects
- Review of inspection history and examination effectiveness
- Survey of components and selection of representative components for analysis
- Evaluation of potential degradation mechanisms
- Component stress analysis

Once the above steps were completed, components are subjected to Deterministic and Probabilistic Fracture Mechanics Evaluations. The DFM and PFM approaches used in the EPRI reports are based on methods used in previous inspection optimization projects, and involved either an increase in examination interval, a reduction in examination scope, or both. The DFM evaluations were performed using bounding inputs to determine the length of acceptable component operability with a postulated flaw. The results of the DFM investigation were also to determine the critical stress paths for consideration in the PFM analyses. The results of the DFM evaluations concluded that all selected components are very flaw tolerant, with the capability of operating with a postulated flaw for more than 80 years.

PFM evaluations were performed to demonstrate the reliability of each selected component assuming various inspection scenarios (e.g., preservice inspection (PSI) only, PSI followed by 10-year in-service inspections (ISI), etc.). Monte Carlo probabilistic analysis techniques were used to determine the effect of randomized inputs and various inspection scenarios on the probabilities of rupture and leakage for the selected components. Sensitivity studies are performed to investigate possible variation in the various input parameters to establish the key parameters that most influence the results.

For each component, probabilities of rupture and leakage were determined for the limiting stress paths in each selected component for a variety of inspection scenarios. The results of the PFM evaluations demonstrated that the NRC acceptance criteria of 1.0E-6 for both probabilities of rupture and leakage could be maintained for all components for inspection intervals longer than the 10-year intervals defined in Section XI of the ASME Code. Therefore, the results demonstrate that examinations for the selected components can be extended beyond current the ASME Code-defined interval; in some cases, they can be extended out to the end of the current licensed operating period (at least 30 years for most plants).

Why Structural Integrity

SI is the primary author of the four EPRI Reports cited above (3002014590, 3002015906, 3002015905 and 3002018473). The inspection optimization projects have provided SI with the opportunity to use its experience in structural reliability to develop a customized PFM software tool named **PROMISE** (**PR**obablistic **O**pti**M**ization of **I**n**S**p**E**ction), which was used to optimize the inspection schedules for various plant components. The **PROMISE** software implemented a probabilistic model of fatigue crack growth using linear elastic fracture mechanics (LEFM) methods, consistent with ASME code, Section XI flaw evaluation procedures.

The software was developed, verified & validated (V&V), and tested under the provisions of a 10 CFR 50, Appendix B Nuclear Quality Assurance Program. This tool is based on other, similar previous software codes, and it can be used for similar applications in the nuclear industry where a rigorous technical basis is required to optimize inspection schedules for high-reliability components involving significant outage impact. In 2020, the NRC staff conducted an audit of **PROMISE**.

According to the conclusion of the audit report (ML20258A002), the NRC staff gained a better understanding of how PFM principles were implemented in **PROMISE** and of the V&V on the software.

In addition to the software audit, SI has supported EPRI and industry in developing responses to NRC requests for additional information (RAIs) for the pilot plant submittals for all four EPRI Reports. This experience has given SI a great deal of understanding regarding the most efficient and effective way to preemptively address potential NRC concerns in future plant-specific submittals.

How It Would Work For You

For plant owners to use the technical bases established by this work to obtain relief for their plant, they must demonstrate that the representative geometries, materials, and loading conditions used for the selected components bound their plant-specific information. Based on this analysis, the EPRI Reports provide criteria for each component regarding the component configuration, component dimensions, component materials, applicable transient loadings, and other relevant parameters that must be satisfied on a plant-specific basis. If all criteria are satisfied on a plant-specific basis for a given component, the results of the investigation can be used for the plant as the technical basis to establish revised inspection schedules for that component. If any criteria are not satisfied, then plant-specific analysis is required to address any unbounded conditions. SI can provide support in several areas, including:

- Evaluation of plant-specific parameters against report criteria to determine whether a given plant configuration is bounded
- Performing plant-specific analysis (e.g., component stress analysis, DFM and PFM, etc.) required to address any unbounded conditions
- Supporting development of the relief request to proactively address known NRC areas of concern
- Supporting development of responses to any NRC requests for additional information

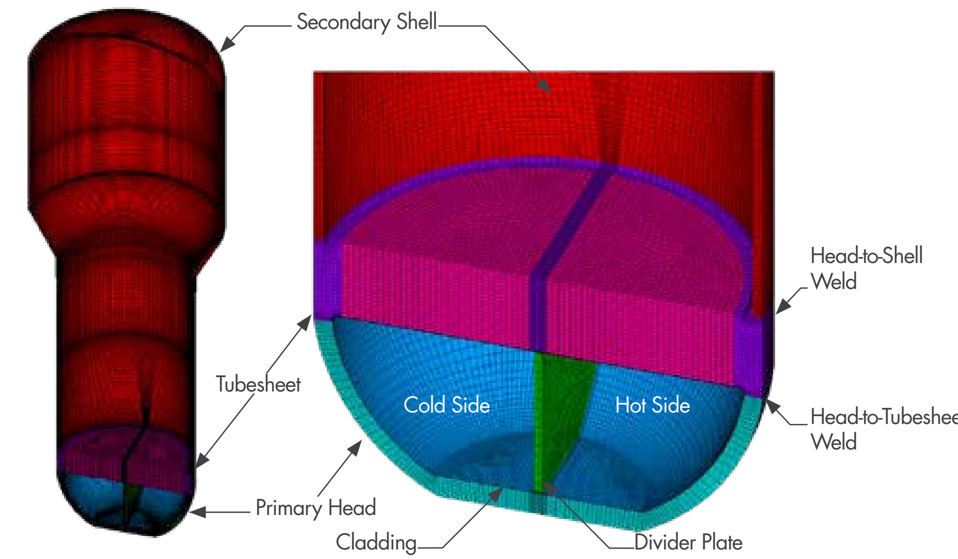
Since the technical basis in the EPRI Reports used generic plant configurations, some plant configurations were not included in the analysis. SI can also support efforts by plants with such configurations to determine whether they are bounded by the criteria of the EPRI Reports.

Plant Experience To Date

The first plant-specific submittal was made by a U.S. two-unit PWR site in December 2019 based on EPRI Report 3002014590, requesting an inspection alternative to current ASME Code, Section XI examination requirements for steam generator main steam and feedwater nozzle-to-shell weld and inner radii examinations. The alternative requests an increase in the inspection interval for these items from 10 to 30 years. The safety evaluation report (SER) for this alternative was received from the NRC in January 2021.

The first plant-specific submittal was made by a U.S. PWR site in December 2019 based on EPRI Report 3002015906, requesting an inspection alternative to current ASME Code, Section XI examination requirements for steam generator Class 1 nozzle-to-vessel welds and Class 2 vessel head, shell, tubesheet-to-head, and tubesheet-to-shell welds. The alternative requests an increase in the inspection interval for these items from 10 to 30 years. RAIs for this alternative were received from the NRC in February 2021. SI supported development of the RAI responses.

The first plant-specific submittal was made by a U.S. two-unit PWR site in December 2019 based on EPRI Report 3002015905, requesting an inspection alternative to current ASME Code,



Section XI examination requirements for Pressurizer Head, Shell-to-Head, and Nozzle-to-Vessel Welds. The alternative requests an increase in the inspection frequency for these items from 10 to 30 years. RAIs for this alternative were received from the NRC in February 2021. SI supported development of the RAI responses.

The first plant-specific submittal was made by a U.S. two-unit BWR site in December 2019 based on EPRI Report 3002018473, requesting an inspection alternative to current ASME Code, Section XI examination requirements for Class 2 BWR heat exchanger nozzle-to-shell welds; nozzle inside radius sections; and vessel head, shell, and tubesheet-to-shell welds. The alternative requests an increase in the inspection interval for these items from 10 years to the end of the plant's current operating license. RAIs for this alternative were received from the NRC in February 2021. SI supported development of the RAI responses.

Conclusion

Inspection optimization offers the opportunity to reallocate plant resources to higher value activities. In a highly competitive electricity market, the work here has shown opportunity exists to improve O&M costs and maintain safety through effective analysis.

SI brings to bear the prior experience in developing the methodology with EPRI, proprietary NQA-1 verified software, and decades of industry credibility to support all aspects of the efforts required to institute a program of inspection optimization.

Please contact Scott Chesworth at SI (schesworth@structint.com or 408-833-7295) or Bob Grizzi at EPRI (rgrizzi@epri.com or 704-595-2511) if you would like to learn more about component examination optimizations.

Autobook

Nuclear Physics Automation Code

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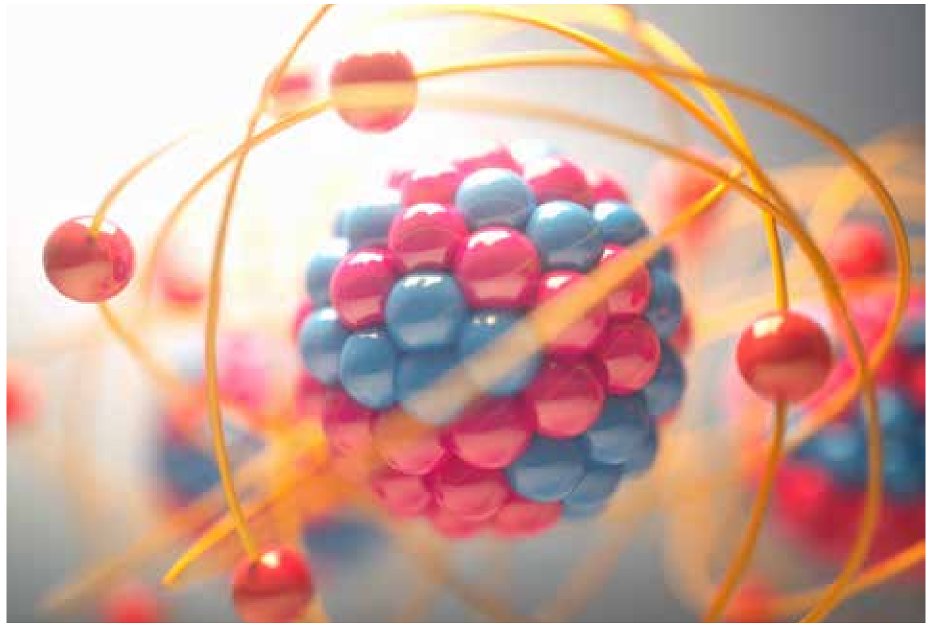
The AUTOBOOK code reduces human errors, increases efficiency, and streamlines the reload analysis process

AUTOBOOK facilitates plant operation by providing nuclear power plant Reactor Engineers and Reactor Operators with cycle-specific information about the physics characteristics of the reactor core in a core data book document. Structural Integrity has created the AUTOBOOK computer code to automate the creation of this document.



AUTOBOOK is a Quality Assured code developed under a licensee's software quality assurance (SQA) program. SI provides a full complement of SQA documents, including a Software Requirement Specification (SRS), a Software Design Description (SDD), Verification and Validation (V&V) Plan and Test Report, a User Manual, and Software Installation Instructions (SII).

AUTOBOOK is designed to provide the user with ease of use, multiple options, and a code modularity that facilitates future code enhancements. Figure 1 depicts the AUTOBOOK process flow diagram.

The AUTOBOOK design allows the user to analyze various reactor core configurations. AUTOBOOK can analyze fuel with or without a burnable poison such as erbia or gadolinia, and with or without an Integral Fuel Burnable Absorber (IFBA) such as zirconium diboride. AUTOBOOK can analyze numerous fuel cycle times-in-life including beginning of cycle, middle of cycle, and end of cycle operations. In the presence of an IFBA, AUTOBOOK can generate results for the burnup associated with the peak Critical Boron Concentration of the cycle.

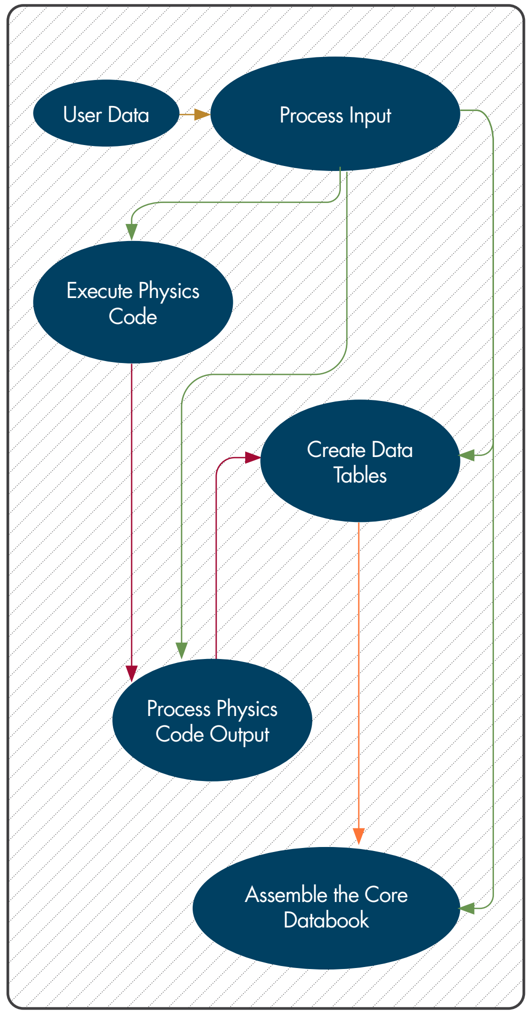


FIGURE 1. Autobook process diagram

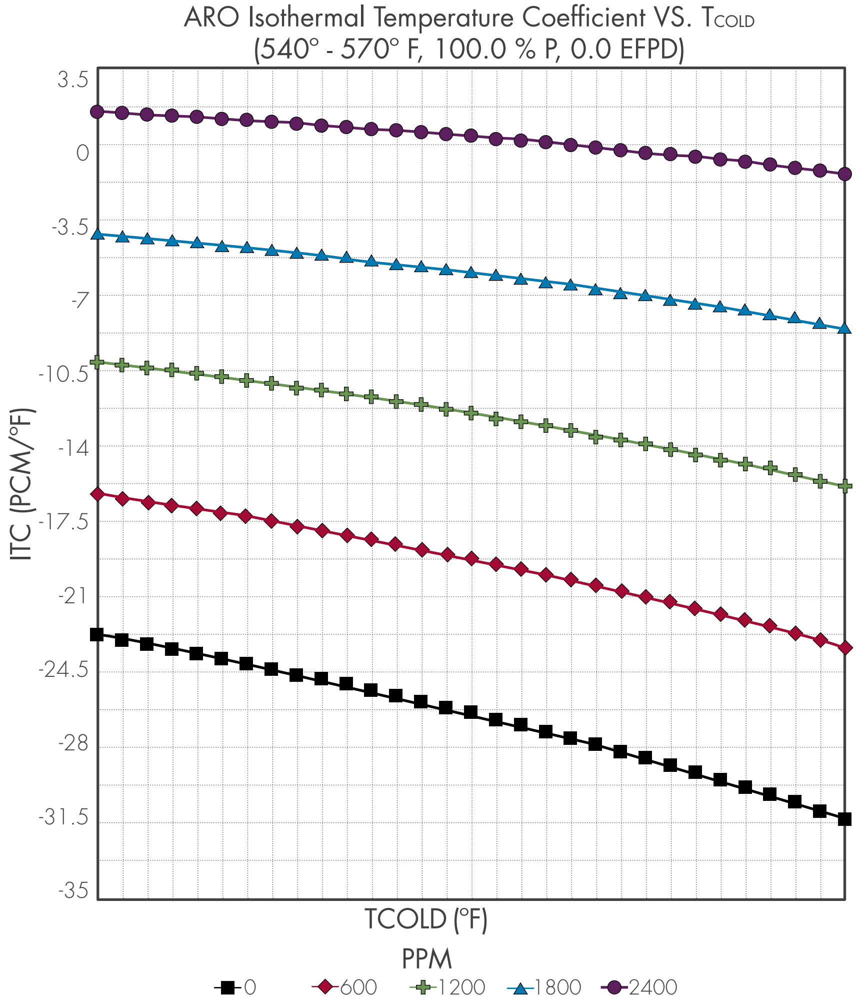


FIGURE 2. Typical Autobook generated data plot

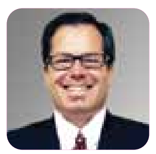
A typical core data book is composed of more than 200 pages of text, data tables, and data plots. Figure 2 presents a typical AUTOBOOK data plot.

AUTOBOOK is part of SI's on-going innovation effort to improve plant operations and maintenance. Through automation, AUTOBOOK can quickly create a core data book that was a time-intensive reload analysis task. AUTOBOOK reduces human errors, increases efficiency, and streamlines the reload analysis process by converting a multi-step process with analyst intervention into a single-step process.

AUTOBOOK transforms what is a multi-week core data book origination task into a one or two day task. The shortened preparation time allows the origination effort to begin after the completion of the current operating cycle. Should a core redesign be needed during a refueling outage, AUTOBOOK significantly enhances the ability to respond to the plant needs and avoid extending the outage duration.

PEGASUS©

Advanced Tool for Assessing Pellet-Cladding Interaction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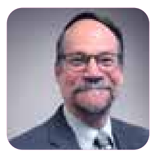
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PEGASUS provides a fully capable computational environment to solve the unique, detailed 3D analyses required for the evaluation of PCI.

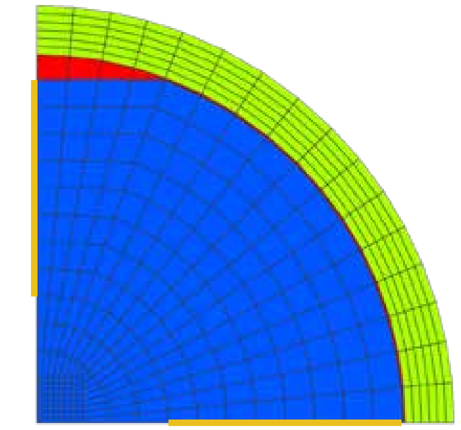


FIGURE 2. 2D Mesh Showing an MPS Superimposed on a PCI Model (Pellet Cracks are Modeled on the 0° and 90° Lines of Symmetry)

In the current economic environment in which nuclear units compete with less costly energy sources, a quicker return to full power correlates to more power generated and increased operating efficiency. This may be achieved with shorter startup post-refueling or a quicker return-to-power following any number of plant evolutions including load follow, control blade repositioning, equipment outage or maintenance, testing, extended low power operation, scram, etc. Such strategies to increase operating efficiency may enhance the risk of pellet-cladding interaction (PCI), a failure mechanism that occurs under conditions of high local cladding stress in conjunction with the presence of aggressive chemical fission product species present at the cladding inner surface. These conditions can occur during rapid and extensive local power changes and can be further enhanced by the presence of fuel pellet defects (e.g., missing pellet surface, MPS). Several commercial reactor fuel failure events in the last eight years, as recently as early 2019, suggest a PCI-type failure cause. To safely manage changes in core operation, the margin to conditions leading to PCI-type failures must be determined prior to implementation of such operating changes.

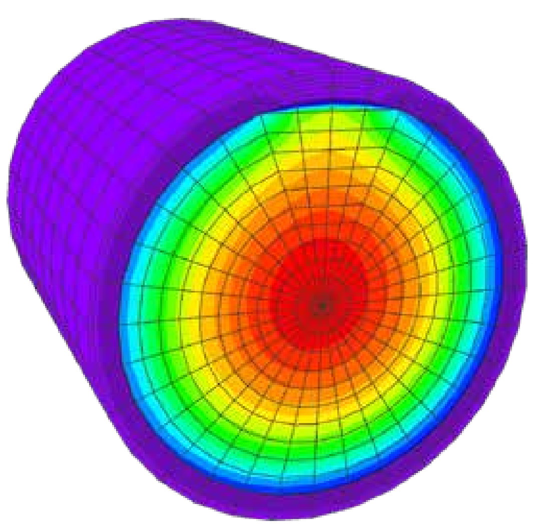


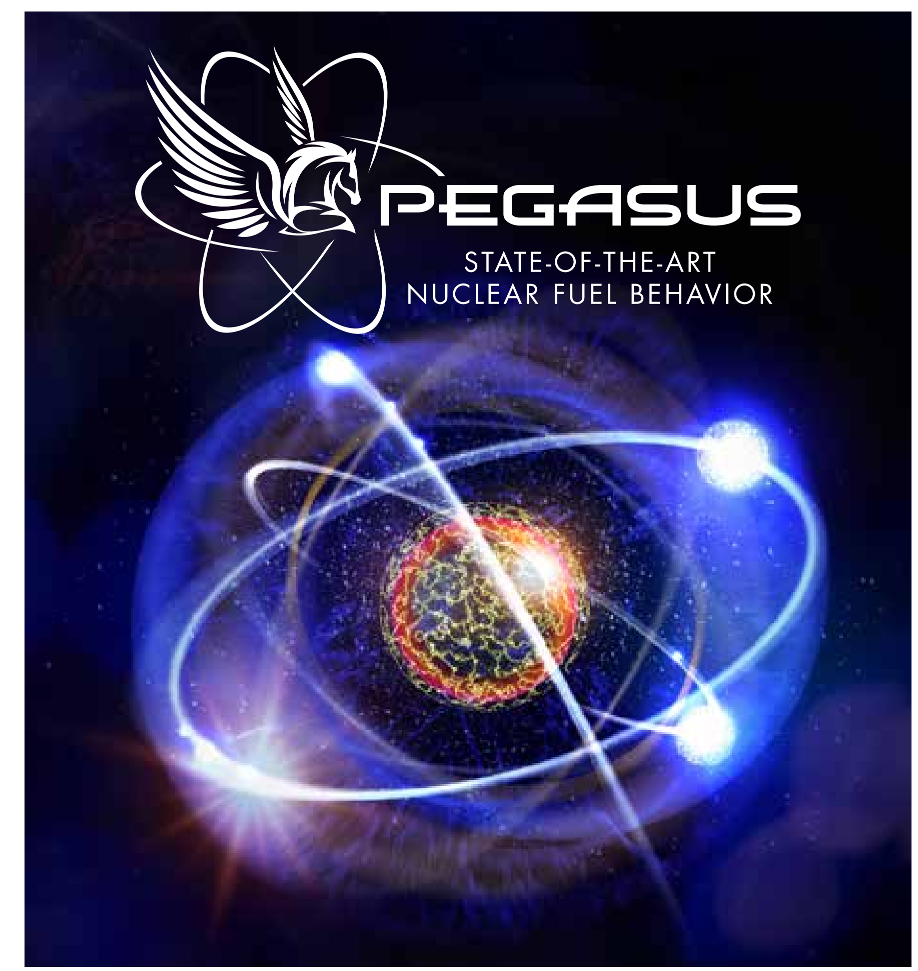
FIGURE 1. 3D Model Showing Temperature Distribution in a Pellet with an MPS Defect

Technical aspects leading to PCI are quite complex and require performance of high-fidelity simulations using an advanced fuel performance code to determine the integral thermal, mechanical, and chemical aspects of the failure mechanism. The PEGASUS nuclear behavior code is such a tool featuring a non-linear thermo-mechanics simulation platform with a unique and robust 3D modeling computational foundation. Coupled to the requisite nuclear material constitutive models, PEGASUS provides a fully capable computational environment to solve the unique, detailed 3D analyses required for the evaluation of PCI.

Critical to the assessment of PCI margin under planned operational conditions is the development of PEGASUS-specific fuel failure thresholds. These will be developed based on an extensive database of experimental fuel rods tested under a variety of power ramp rates and conditioning and ramp terminal power levels. Utility-specific analyses can be performed to accommodate fuel design features and core operational strategies that vary from utility to utility. The analyses will explicitly define proposed operational strategies to establish margin-to-failure and operational remedies if inadequate margins are determined.

The next phase of planned development for PEGASUS is focused on support for advanced technology fuels such as those proposed for next generation light water, gas-cooled, and molten salt reactors. These proposed designs encompass full-size, small modular, and micro reactor systems and include silicon-carbide cladding, coated cladding, metallic and doped fuels, HALEU, TRISO, and other proposed advanced fuel types.

To learn more visit
www.structint.com/pegasus/
or contact us at
info@structint.com



Mission Critical Applications to Support the Mega-Rule

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On October 1, 2019, the Pipeline and Hazardous Materials Safety Administration (PHMSA) published amendments to 49 CFR Parts 191 and 192 in the Federal Register, issuing Part 1 of the Gas Transmission Mega-Rule. This new regulation is commonly referred to as the Mega-Rule since it represents the most significant regulatory impact on gas transmission pipelines since the original Gas Transmission Integrity Management Program (TIMP) Regulation was issued in 2003

The original Notice of Proposed Rulemaking (NPRM) issued in April, 2016 was split into 3 Parts, with the first Part (Mega-Rule 1) including specific requirements to address congressional mandates in the 2012 Pipeline Safety Reauthorization, and other pipeline safety improvements, including:

- Maximum Allowable Operating Pressure (MAOP) Reconfirmation (§192.624),
- Material Verification (MV) (§192.607),
- Engineering Critical Assessments for MAOP Reconfirmation (§192.632),
- Analysis of Predicted Failure Pressure (§192.712),
- Assessments Outside of High Consequence Areas (HCAs) (§192.710),
- Additional Requirements to Evaluate Cyclic Fatigue (§192.917(e)(2)), and
- Additional Analysis of Electric Resistance Welded (ERW) Seam Welds (§192.917(e)(4))

To help clients comply with these regulatory requirements, Structural Integrity has developed specific applications within our Asset Integrity Management System (AIMS™) platform, a configurable, cloud-based system for implementing asset management programs such as pipeline integrity. The AIMS platform includes multiple applications to address specific integrity management and Mega-Rule compliance support. The following are some of the specific applications:

MAOP Reconfirmation: This application evaluates the adequacy and status (i.e. *Traceable, Verifiable and Complete* (TV&C)) of records used to establish MAOP. It does so by creating traceable links between the records provided, the data extracted from them,

Continued on next page

and a geospatial representation of the asset. Users can easily link a pdf document to a pipeline segment through a geospatial interface. Relevant data, such as test pressure or test duration, can be linked to the document. Through this process, the application can assess the robustness of MAOP records and link the key attributes within each record type to a specific pipeline segment, component, and/or pipe population. Algorithms and reporting tools have been integrated to identify mileage and segments that are required to be incorporated in MAOP Reconfirmation and/or Material Verification Programs. The application is highly configurable to support an operator's data management, operational, and security requirements. Reconfirmation plans and schedules can be established and monitored to track status through the MAOP Reconfirmation Program.

Assessment Planning: The Assessment Planning Application helps operators manage Transmission Integrity Management Program (TIMP) Assessments for covered segments and Assessments Outside of HCAs. Operators are now managing assessment plans for HCAs, Moderate Consequence Areas (MCAs), actionable Class 3 or 4 Locations, and casings – far more than before the Mega-Rule. In the app, each segment has the assessment history and future assessments identified in a single application that is linked to the applicable project. Operators have found this capability valuable to ensure that assessment deadlines are not missed, even when faced with project delays. The history of HCA splits, merges, and renames is tracked and viewable in a graphical format – a helpful resource when HCA names have changed over the course of a TIMP. The dashboard and notification capability help to prompt action if a deadline is in danger of being missed. Finally, detailed reporting capabilities can provide thorough and auditable records in pdf or spreadsheet formats.

Material Verification Intelligence (MVI): The Material Verification (MV) requirements of the Mega-Rule introduce operational complexity – operators must decide where and how to pursue MV, while complying with 192.607 regulations and FAQs. Structural Integrity has developed a new tool, MVI, as a web-based application that can help make decisions and organize essential data to ensure implementation is aligned with supporting MV procedures. MVI is intended to help operators with two main strategic goals: efficiency and compliance. MVI helps facilitate data collection, analysis, and documentation. The app automates the comparison of MV results to specified values, notifies individuals on availability of information (including inconsistencies identified) and provides an intuitive dashboard to view key performance indicators and results. Full pdf documentation can be generated to demonstrate MV Program compliance.

Additional Mega-Rule1 Compliance Tools: In addition to the AIMS platform applications, Structural Integrity has developed several additional capabilities, procedures, tools and programs to provide Mega-Rule compliance support for our clients, including the following:

- Engineering critical assessment procedures in support of MAOP reconfirmation,
- Predicted failure pressure analysis procedures and tools,
- Detailed MV procedures and position papers on expanded and alternative sampling,
- Transmission pipeline system cyclic fatigue analysis,
- Digital elevation modeling to determine whether elevation during a Subpart J pressure test must be considered significant (in accordance with record requirements specified in §192.517)

In response to the Mega-Rule 1 requirements, SI is pleased to provide our gas transmission pipeline clients with these additional mission critical applications, capabilities, programs and tools to assist clients in complying with the new regulation in the most safe and effective manner possible. Please contact Structural Integrity if you would like to discuss any of these innovative new offerings.

VOLUME 49 | **NEWS AND VIEWS** | OIL & GAS

Digital Elevation Modeling

Support Pressure Tests Records and Reduce MAOP Reconfirmation Costs

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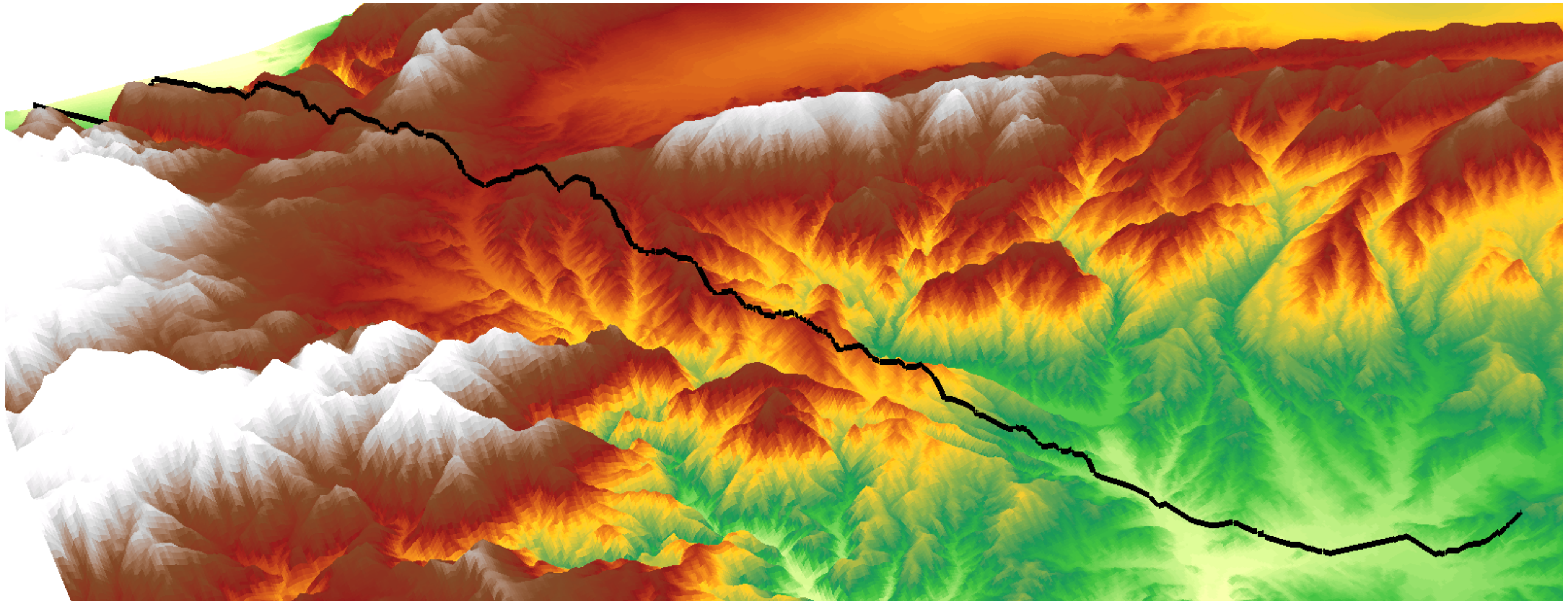
§ 192.624(a)(1) of the Mega-Rule 1 requires MAOP Reconfirmation for steel transmission pipe segments if records necessary to establish the MAOP in accordance with § 192.619(a)(2) (e.g. pressure test), including records required by § 192.517(a), are not traceable, verifiable, and complete and the pipeline is located in a high consequence area (HCA) or a Class 3 or Class 4 location.



Part 192, Section 192.517(a) requires that natural gas pipeline operators shall make and retain, for the useful life of the pipeline, a record of the following information for any Subpart J Pressure Test (PT):

1. The operator's name, the name of the operator's employee responsible for making the test, and the name of any test company used,
2. Test medium used,
3. Test pressur,
4. Test duration,
5. Pressure recording charts, or other record of pressure readings.
6. Elevation variations, whenever significant for the particular test, and
7. Leaks and failures noted and their disposition.

It is not uncommon for PT records to be missing certain information from the required list. Although certain information may be unavailable on select segments, a PT record missing specific information, such as elevation data, can be analyzed retroactively to make a determination whether elevation must be considered significant for the pressure test, and in addition, the potential impacts of considering the elevation.

In some cases, the elevation variations (if any) along the length of the pipeline may not be addressed or recorded in the PT documentation. This is presumably due to the fact that the elevation was not considered significant for the respective pressure test. In cases when elevation variations are not documented for a pressure test, rather than discarding the pressure test as not TV&C, Geographic Information System (GIS) can be used to determine the elevation variation after the fact and confirming that elevation is not a relevant factor in the pressure test. This can help to provide more complete documentation of the §192.517 requirements and further help establish traceable, verifiable and complete (TV&C) record status.

SI has developed specific programs and tools to analyze each pipeline segment's elevation variation records. The steps in this analysis include:

- Reviewing a select segment's PT records and missing elevation data,
- Analyzing PT segment lengths and establishing pipeline extents based on key PT factors,
- Completing a digital elevation model of the pipeline,
- For each PT segment, conservatively evaluating the potential hydrostatic head impact, and
- For each PT extent, determine whether elevation is deemed significant and whether the required pressure test factor (per § 192.619) for the respective Class Location was maintained.

Programs and tools, such as elevation analysis discussed above, can have a significant influence on TV&C record status and potentially greatly reduce the pipeline mileage that may be considered in scope for MAOP Reconfirmation and the associated costs.

Code Compliance and the Modular Construction Trend

What Manufacturers Need to Know to Comply with Building Codes

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The modular construction industry is projected to grow globally at an annual rate of 6.9%, outpacing the growth of traditional construction.[1] Modular construction has many advantages over traditional building methods, including improved quality control and shorter project durations. Factory-built systems are constructed in controlled environments with equipment and materials that are not feasible at congested job sites, and project schedules can be shortened when factory work and field work are performed in parallel.

However, modular projects may stumble without proper forethought: when fabrication takes place in a factory away from the jobsite, the building officials, inspectors, and engineers can have less oversight and less recourse to implement changes if issues are discovered in the field. Code compliance may also be an issue when systems are designed by factory engineers rather than the engineer of record. To mitigate these potential pitfalls, careful planning is required at the start of the project.

SAME INSPECTIONS, DIFFERENT LOCALE

FIGURE 1. Lifting of Modular Central utility plant at Scripps Green Hospital, San Diego, California

Unlike field-built systems, where the structural system is designed 'from scratch' for each project and the materials selected for the project are dependent on local availability, in a modular system the manufacturer already has a carefully configured structural system designed to optimize the performance of the system on a variety of factors including space efficiency, fabrication cost, and constructability.

Rather than selecting the structural system, the structural engineer qualifying the modular system starts by checking the existing system for the required loads and detailing requirements of the local building code, recommending strengthening wherever necessary. Drawings documenting the construction can be produced by the manufacturer or by the structural engineer, or in some cases both. These drawings serve the dual purpose of communicating to factory personnel the construction methods and required details to meet local requirements, and to summarize mandated inspections and observations. Inspection and observation requirements of the International Building Code apply even if the construction is completed thousands of miles from the jobsite.

To ensure the construction is following applicable codes, the eventual owner will select a licensed building inspector qualified to oversee the fabrication at the factory. Typically, this professional will live in the region near the factory and will visit the factory at periodic intervals as key components are fabricated. Similarly, the structural engineer will visit the factory to perform construction observations, as required by code, or designate a qualified alternate to complete the required observations.

By the time the fabrication is ready to be shipped, a majority of the required inspections and observations will have been completed at the factory and only a few remaining checks will be required at the project site. These final inspections are typically related to connections, e.g., where the modular components are connected to one another in the field, or anchorage, e.g., where the modular components are anchored to the site foundation.

FIGURE 2. Modular air handling unit undergoing seismic testing

PROJECT SPECIFIC DESIGN OR CERTIFICATE OF COMPLIANCE?

For modular systems, the International Building Code allows a manufacturer to either procure engineering services from a licensed structural engineer, as described above, or to issue a Certificate of Compliance for seismic compliance. The certification is analogous to those issued for electrical safety, mechanical performance, fire safety, and other disciplines as well as other structural performance such as wind. The certificate must be based on a products certification from an "Approved Agency" accepted by the building official.

Since 2019, SI's in-house product certification agency TRU Compliance (www.trucompliance.com) has been IAS Accredited to the international standard for certification bodies, ISO/IEC 17065, and has been accepted as an Approved Agency by building officials nationwide. Certification engineers at TRU complete engineering analysis and testing on a variety of modular systems and provide certifications documenting seismic accelerations and wind pressures the product can withstand. In some cases, TRU engineers work with manufacturers to assess strengthening options so products can withstand higher loads and achieve higher levels of load certification. Customizable product lines require certification documents with restrictions clearly outlined, restrictions which are necessary for the products targeted performance level to be met. After issuance of the certification document, the manufacturer can fabricate and install the certified product at unlimited locations as long as they follow the guidelines, label the product as TRU Certified with traceable reference numbers, and submit all documents to the project team at each site. They must also submit to regular surveillance by TRU inspectors and are subject to periodic renewal of their certification after TRU confirms the product, process, and management system are still in compliance. In following this process, the building officials are effectively delegating the code compliance checks to Approved Agencies like TRU.

FIGURE 3. Modular bathroom being installed at wilshire grand hotel, Los Angeles[2]

Clearly, the certification approach has many advantages to manufacturers, but it is limited to products with set designs and configurations. Often a design of a modular system is very unique to a specific project and it is not feasible to find a certification method that encompasses all possible designs. In such cases, engineering and inspection specific to a site are required.

WHAT'S NEXT

With modular construction projected to grow faster than traditional construction, the scope of its adoption appears to be constrained only by the size of modules that can be shipped on our highways. Beyond central utility plants, the modular construction is being applied to bathrooms, apartments, office pods, and even high-rise towers. Recently, the Wilshire Grand Hotel in Los Angeles was completed using premanufactured bathrooms constructed in a factory in Florida. This approach allowed the tallest building west of the Mississippi River to be constructed faster than what traditional methods would permit, and to the high quality standard expected of a luxury hotel.

As the world's construction methods change, codes will eventually evolve too. In the meantime, a proven method to allow modular systems to comply with existing codes needs to be followed to help deliver the speed, efficiency, and quality promised by modular construction.

SI EXPERIENCE

Structural Integrity Associates (SI) has successfully designed modular central utility plants in restrictive jurisdictions like the California Office of Statewide Health Planning and Development (OSHPD), which serves as a de facto building department for all acute care hospitals in California. In the early 2010's, SI's legacy company completed the structural design and oversaw installation of the first modular central utility plant at a California hospital, Tahoe Forest Hospital. The plant was fabricated offsite and assembled in pieces at the final location in Truckee, California. Since then, SI has designed and overseen the design of numerous modular central utility plants across California at locations such as Scripps Green Hospital in San Diego, Lucile Packard Children's Hospital in Palo Alto, and Los Angeles Mission College.

Footnotes

(1) Modular Construction - Global Market Trajectory & Analytics. ResearchandMarkets.com. September 2020.

(2) Ufberg, Ross. "Plug, Play and Flush: Why modular bathrooms are gaining in popularity." Built, The Bluebeam Blog. October 11, 2017. <https://blog.bluebeam.com/plug-play-flush/>

(3) Photo by SHoP Architects. Obtained via dezeen magazine https://www.dezeen.com/2016/11/18/worlds-tallest-modular-prefabricated-apartment-tower-shop-architects-brooklyn-new-york/

FIGURE 4. RIGHT Modular Apartment High-Rise in Brooklyn[3]

VOLUME 49 | **NEWS AND VIEWS** | CRITICAL INFRASTRUCTURE

The 4th Dimension

Lifecycle Assessment of Critical Structures

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AGING INFRASTRUCTURE ISSUES

The infrastructure in the United States is aging and, whether publicly or privately owned, significant resources are required to repair, replace, or modernize it. Due to the high costs associated with these efforts, owners need to identify structures with high risk-of-failure consequences and find the most cost-effective solutions for rehabilitation. High consequence infrastructure includes:

- Highway and railway bridges,
- Roadways for intra and interstate transportation,
- Dams, locks, and levees for flood control and cargo transportation,
- High rise business, apartment, and condominium towers, and
- Power generation and distribution facilities for Nuclear, Fossil and Hydro utilities.

All infrastructure, is susceptible to degradation that comes with aging. The accumulation of degradation, and a structures subsequent failure, is difficult to predict due to the numerous real-world factors that influence rates of degradation. These real-world factors can lead to some structures failing prematurely and others lasting well beyond their original design life. Asset owners need to be on the lookout for:

- A structure that is nearing or has exceeded its expected design life,
- A structure that shows signs of steel corrosion, freeze-thaw damage, or concrete degradation such as alkali aggregate reaction (AAR),
- A structure that is overloaded due to an increase in auto, truck or rail traffic,
- A structure with a known design deficiency when evaluated with modern design code requirements,
- Increases in regional hazards, such as increased seismicity or increased probable maximum flood levels, and other climate change related issues.

Often, structures are kept in service beyond their original design life. Many older structures are held to a design basis, i.e. code requirements, consistent with the time the structure was designed. Evaluating older structures using current code requirements can potentially affect original safety margins both positively and negatively. Increased capacity limits can be established for steel welded and bolted connections and utilizing actual concrete compressive strengths above original design strength that may provide added safety margin. On the other hand, identifying substandard details relative to current practice, particularly concrete reinforcement detailing will reduce originally considered safety margins. Additional factors that can affect the service life of a large infrastructure projects include environmental conditions, reliability of materials, quality of construction, and loading conditions.

Throughout the country, many structures such as bridges, dams, and power generating facilities remain in active service as they approach or exceed their design (or licensed) service life. Replacement is often prohibitive for many of these structures due to cost. However, failure of these structures could have more significant consequences beyond lost revenue, including loss of life.

Identifying structural vulnerabilities and designing retrofit modifications is essential to economically extending the service life of these structures.

CURRENT REGULATIONS

There is no single agency that oversees the various types of infrastructure within the United States. The following structures generally fall under the purview of these agencies:

- Bridges, Roadways and Railways - National Transportation Safety Board, Federal Highway Administration, State Level Departments of Transportation, and some local City Departments of Transportation
- Nuclear Facilities - Nuclear Regulatory Commission (NRC), US Department of Energy
- High Rise Buildings - State and Local City Building Departments
- Dams for Hydroelectric and Water Storage - Federal Energy Regulatory Commission (FERC), State Level Dam Safety Departments

> By analytically simulating the steps in the construction process, including the sequence of concrete placements, and tracking the history of the material behavior starting from initial placement, the potential for cracking is evaluated by comparing the time dependent stress and strains to the concrete cracking resistance and capacity.

At a high level the different regulatory bodies have a common mission to keep asset owners accountable to maintaining the mandated level of safety for the general public. Different regulations and procedures are required depending on the type of project, owner, and overseeing agency involved.

LIFECYCLE OF A STRUCTURE

As structures reach the end of their design service lives or are in extended service, regulators typically require asset owners to demonstrate that these structures can still maintain their functionality while posing a low risk to the public safety, regardless of expense to the owner. Thus, it is beneficial for the owner to perform maintenance to ensure safe and functional assets that are profit positive, versus the potentially large costs incurred during decommissioning, removal and remediation of project sites.

Lifecycle structural health monitoring and simulation is a methodology to track changes in a structure that occur during the structures service life. Monitoring can be performed through non-destructive examination techniques. Continuous health monitoring helps owners maintain their assets by providing a warning if a sudden change or degradation accumulation is observed. This data can feed desktop simulations which incorporate the time variable into the modeling of the asset, giving point-in-time snapshots of how the structure behaves under loading during different stages of its life.

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PREDICTING DEGRADATION: DURING DESIGN

During the design phase, large infrastructure projects are designed for a variety of expected loads including thermal load cycles, live loads, and operational loads. Seldom is the cumulative impact of cyclic loading considered when estimating the expected service life of the structure. Incorporating transient seismic demands or some other unexpected blast, shock or impact loading in combination with the expected stress range that occurs in structural components the lifecycle endurance limit can be evaluated that may be different from originally established design basis limits. For example, concrete degradation typically manifests itself as cracking, sometimes occurring in unexpected locations. Cracking can allow water infiltration, leading to internal corrosion of reinforcement and corrosive swelling, which can weaken the structure and accelerate degradation. In cold environments repeated freeze-thaw cycles will further damage the concrete.

Cumulative damage not only affects the loss of static strength, but will also change the dynamic characteristics of the structure. This can lead to the poor performance of a structure supporting vibrating equipment or a structure subjected to seismic loading. By incorporating the effects of damage accumulation in a structural assessment, the time-varying dynamic characteristics of the structure can be identified. Incorporating these effects as part of a lifecycle assessment can provide the owner with a more realistic understanding of actual structural condition of their asset that can guide targeted remediations (i.e. mitigate excess equipment vibration) or alert the owner to an increased risk of failure under a postulated seismic event.

PREDICTING DEGRADATION: DURING CONSTRUCTION

During construction of mass concrete structures large temperatures develop due to concrete curing. A Nonlinear Incremental Segmental Analysis (NISA) evaluates the thermal and static loading of young concrete to determine the potential for cracking. The propensity for cracking depends on the concrete mix, environment, and boundary conditions imposed during construction. The concrete temperature varies with time and depends on the volume and rate of concrete placement, the sequence and geometry of the placements, the concrete placement temperature and heat generation rate, and the ambient conditions. The boundary conditions imposed during construction depend on the sequence and geometry of the placements, the interaction with the foundation/formwork and any adjacent or embedded structures, and the time dependent aging, creep, and shrinkage properties of the already placed concrete lifts. To accurately account for all of these factors, the NISA must be capable of representing a coupled thermal-mechanical analysis with nonlinear material properties. By analytically simulating the steps in the construction process, including the sequence of concrete placements, and tracking the history of the material behavior starting from initial placement, the potential for cracking is evaluated by comparing the time dependent stress and strains to the concrete cracking resistance and capacity. The cracking resistance is constant for any mature concrete present, such as pre-cast concrete forms, but is time dependent for the freshly placed young concrete since the tensile strength and modulus are changing as the concrete hardens and ages.

PREDICTING DEGRADATION: DURING SERVICE

A concrete structure often has predictable and repeating loading patterns over the course of its service life. For instance, a dam will reliably have high and low water levels throughout the year, though the actual levels may depend on the weather in a given year. A bridge will reliably experience different load patterns in weekday versus weekend traffic. A nuclear containment structure will experience thermal load cycles during power generation operation and shutdown for planned outages.

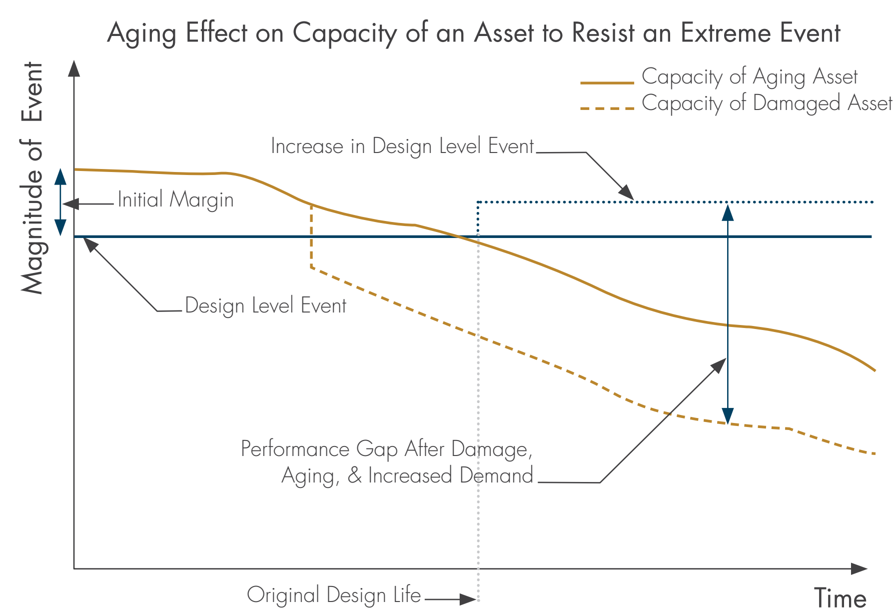

FIGURE 1. Aging Structures and Decreasing Margin of Safety

FIGURE 2. Concrete arch dam circa 1909, aging degradation Issues subject to increased flood and seismic demands

FIGURE 3. Concrete placement with active cooling to reduce concrete heat generation

When looking into the future, engineers make reasonable predictions of different loading events during the initial design phase of a structure. Supplementing these prediction methods with sensor data and observed damage from onsite can help predict the time where the structure goes from safe to unsafe and remedial measures need to be taken. Sophisticated concrete material models, such as SI's proprietary ANACAP model, can incorporate all known forms of time-based concrete behavior such as creep, shrinkage, radiological degradation, cement hydration, alkali aggregate reaction, steel corrosion, scour of concrete, and freeze-thaw cycles. This can further enhance the predicted structural performance during the design basis and extended license period of critical infrastructure as part of an asset owners risk management program.

TIME-DEPENDENT MARGIN

Figure 1 shows the capacity of a structure to resist a large event (such as a flood or earthquake), and how the margin of safety changes over time. Due to safety factors built into design codes, new structures have a minimum margin of safety against failure even when accounting for small design approximations and construction errors. That margin of safety can decrease when a transient event causes damage (e.g. an earthquake, ship impact, or large flood) and as the structure ages and degrades over time. Further reductions in margin can occur as hazards can increase over time, such as when flood events become more common or when new earthquake faults are discovered from geologic mapping. Over a structure's service life, as it accumulates damage from both transient events and aging, the available margin may be much lower than what was originally intended, increasing the risk of catastrophic failure.

ANSWERING TOUGH QUESTIONS

Can an asset survive an earthquake or large flood event today? How big of an event can it survive? Can it survive the same event ten years from now? How does the structural performance change if we put a remedial measure into place? Without remediation, how long until the structure is unsafe? These questions can be answered with time-based structural lifecycle modeling.

Although much of the infrastructure in the USA is already functionally obsolete - or worse: at risk of catastrophic failure - much of it is effectively operating safely beyond its original design life. Finding assets with the highest risk allows owners to prioritize limited funding for rehabilitation and remediation. Lifecycle modeling helps answer those important questions when the key decisions need to be made.

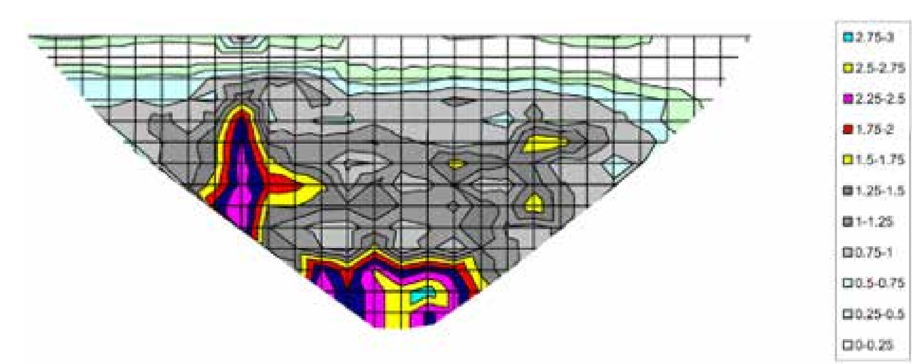

FIGURE 4. Example of Section Loss Contour using High Definition Scanning (HDS), Spectral Analysis of Surface Waves (SASW) and Acoustic Tomography (AT) Methods

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