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Structural Integrity Associates, Inc.®

NEWS & VIEWS

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Encoded Phased Array Ultrasonic Examination Services for CASS Piping Welds

IN PWR REACTOR COOLANT SYSTEMS pg. 8

CEO Message

MARK W. MARANO
President and CEO
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I It has been a pleasure to manage our business in a more normal matter as COVID has finally moved into our rearview mirror. While these effects still linger in our society, and we continue to exercise diligence and prioritize safety, we have appreciated the opportunities to catch up with a number of clients face-to-face. The first half of 2023 has been favorable for Structural Integrity. We are meeting our financial plan despite parts of the business, specifically, our NDE and field services groups, seeing scheduled work shifting into late 2023 or early 2024. More importantly, we are making great strides in developing new offerings and bringing emerging technologies to market, demonstrating our unwavering commitment to our mission as a trusted, independent provider to the energy industry.

In my prior update, I informed you about our new partnership with Jumana. I'm pleased to report that the first seven months have proceeded as anticipated. Jumana continues to fully support our organic and inorganic growth initiatives, allowing us to expand the footprint of our current portfolio while investing in new technology areas. These developments complement our holding company, SI Solutions, and our sister company, C2C Technical Services. Our approach, as always, will be deliberate and thoughtful to ensure it supports our client's needs and maintains the technical expertise and problem engagement you've come to expect from SI.

I encourage you to visit the SI Solutions website: www.SI-SOLNS.com, for a deeper understanding of our approach and offerings, the five market segments we serve, and how we plan to expand this platform and further serve our clients in the future.

Within the past year, we have seen a resurgence in Nuclear Power for all the right reasons, recognizing its significant contribution to the base load power mix in North America and worldwide. As a result, we will see numerous plant life extension and power uprate efforts. We're also seeing rapid development of new plants, with a keen focus on SMRs and advanced Gen-IV reactors, even with the successful commissioning of the first new AP1000 reactor at Plant Vogtle. As the market determines the commercial viability of these various technologies, accelerated engineering support and technology development will be necessary to realize the full benefits of Nuclear energy in our evolving electrical climate.

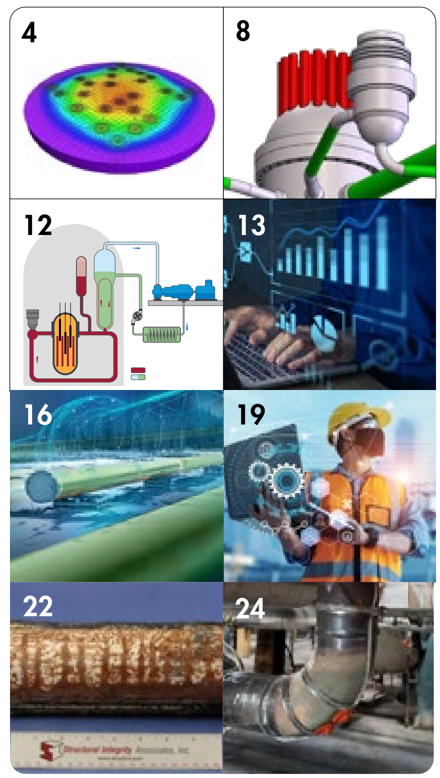
In addition to the good news in Nuclear, other energy sources are seeing exciting developments due to changing market conditions. Operators of combined-cycle units are balancing competitive challenges against a need to ensure the long-term operability of critical assets (e.g., turbine rotors, high energy piping, etc.) by implementing reliability programs. Gas pipeline operators are assessing their ability to blend in hydrogen, reducing the net carbon impact of downstream generation. Critical infrastructure is being tested as record precipitation in portions of the country has filled reservoirs to capacity and brought to the forefront questions on the sustainability of aging assets such as dams and penstocks.

This edition of News & Views continues to demonstrate the excellent breadth of technical solutions and software prowess that SI offers. I hope you will find this to be compelling evidence of the value of partnering with SI as a premier engineering consultant and NDE technology provider. We remain dedicated and focused on helping our clients overcome challenges and achieve sustained success in these evolving times.

I wish you all a great rest of the year, and we will be back with another edition in about 6 months.

Thanks for your support!
Mark

In this Issue



PEGASUS™ Nuclear Fuel Code

Advanced Fuel Modeling Development Status

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INTRODUCTION

The PEGASUS nuclear fuel behavior code features a robust 3D, finite element modeling (FEM) computational foundation capable of performing both thermo-mechanical and structural non-linear analyses within a highly versatile and customizable computational platform. The first applications of PEGASUS were for light water reactor (LWR) fuels and materials. Development work on PEGASUS has been extended to advanced fuel designs such as those proposed for Advanced Technology Fuel (ATF) LWR applications and Gen IV reactor designs, including gas and liquid metal-cooled reactors (GCRs and LMRs).

> The versatility and adaptability of PEGASUS is key in enabling extensions to non-conventional operating environments, materials, fuel forms, and geometries.

LWR APPLICATIONS

SiC Cladding

A project is underway to further the development and irradiation testing of a composite silicon carbide matrix as an ATF cladding material. This research is supported through a DOE Funding Opportunity award (DE-

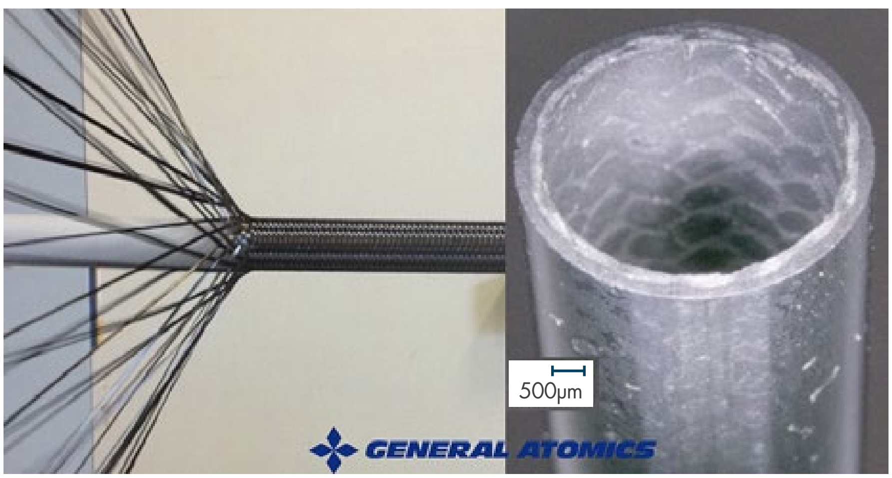

FIGURE 1. SiGA cladding is a multi-layered composite design composed of SiC fiber in a SiC matrix.

FOA-0002308) for the irradiation of a composite silicon-carbide (SiC) ceramic matrix material in an existing U.S. commercial LWR. This work is led by General Atomics – Electromagnetic Systems (GA-EMS) with Structural Integrity Associates (SIA) as a primary subcontractor. For this work, PEGASUS is being adapted to model monolithic and composite SiC manufactured by GA-EMS, SiGA [1], through the incorporation of proprietary material constitutive models. PEGASUS will then be used to provide independent test performance analyses aiding in the design of the irradiation vehicle and predicted material performance. The goal of the testing is to gather irradiation data under prototypic LWR operating conditions and to inform and confirm material performance models for the SiGA-based cladding. A follow-on activity is planned to evaluate the predicted performance compared to data gathered during the post-irradiation examination phase of the project.

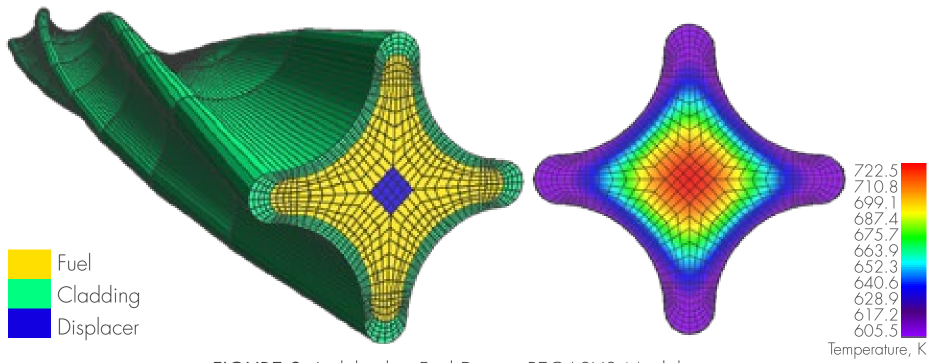

FIGURE 2. Lightbridge Fuel Design PEGASUS Models

Cruciform Metallic Fuel

An additional fuel concept that has been explored using PEGASUS is a cruciform, extruded metallic fuel design proposed by Lightbridge Corporation [2]. This fuel is characterized by a unique multi-lobed fuel cross-section and features a U-50Zr fuel composition. Recent work has been published on fabrication testing of this proposed fuel design by Pacific Northwest National Laboratory (PNNL) [3]. PEGASUS has been used previously to prototype 2D and 3D geometric models and meshes of Lightbridge fuel and to perform fundamental temperature and stress distributions for this fuel under prototypic LWR conditions. PEGASUS has specific modeling tools designed to facilitate "extruded" 3D fuel designs that automate the meshing of these geometries. More work in this area is planned as a proposal has recently been awarded under the DOE NEUP program (DE-FOA-0002732) funding a collaborative project led by Texas A&M University along with Lightbridge, NuScale, and Structural Integrity Associates, Inc. (SI) for modeling this type of fuel for application in a LWR SMR.

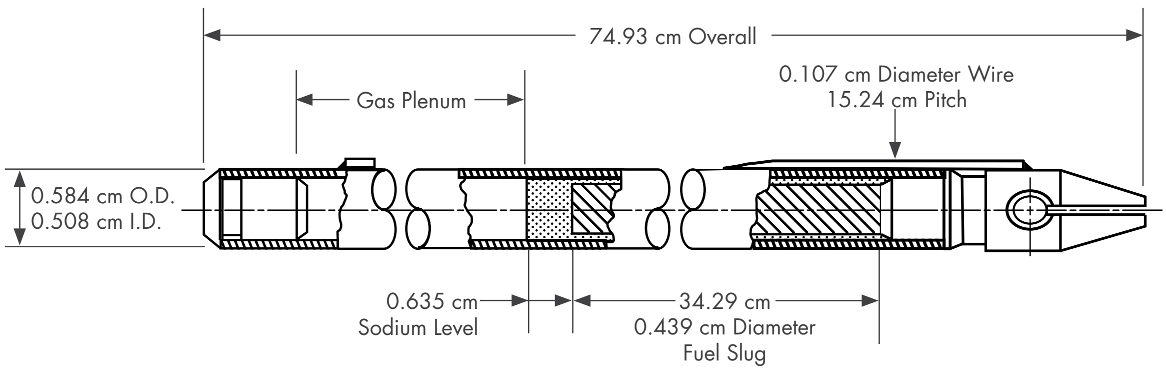

FIGURE 3. Typical EBR-II Mark-III or Mark-IIIA Fuel Element [5]

URANIUM METAL ALLOY FUELS FOR SODIUM-COOLED FAST REACTORS

The initial implementation of metallic alloy fuel and stainless-steel cladding material constitutive models for prototypic fast reactor fuel designs in PEGASUS has been completed. Material properties and behavioral models for U-Pu-Zr fuel and HT-9 (high Chromium, martensitic stainless steel) cladding have been added. Ongoing work includes the implementation of a gaseous swelling and fission gas release behavior model for U-Pu-Zr fuel, a Zr-redistribution model, and a fuel-cladding chemical interaction (FCCI) model that includes the effect on cladding wall thinning.

To test the implementation of these models, benchmark tests were prepared that provided comparative data for assessment of the models' performance. Test cases were chosen from two experimental series irradiated in EBR-II: X430, a 37-pin hexagonal sub-assembly, and X441, a 61-pin bundle.

These experiments were designed to test numerous fuel rod design variables and fuel response as a function of fuel alloy composition, smear density, plenum-to-fuel volume ratio, power, and coolant conditions [4]. The general experimental fuel rod design corresponds to the typical driver fuel configuration shown in Figure 3.

An illustration of the model and selected results from the initial analysis

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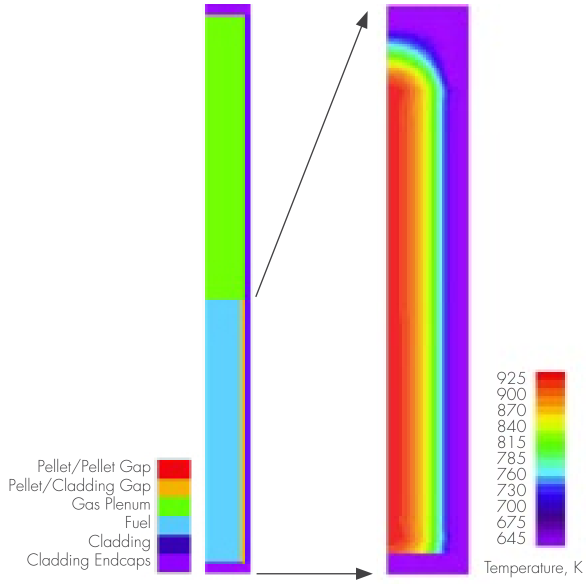

FIGURE 4. Left: 2D Computational Model of Rod DP2, Right: Temperature Contour Plot of the Fuel Stack Region for Rod DP21 at Peak Power (plenum region removed for detail)

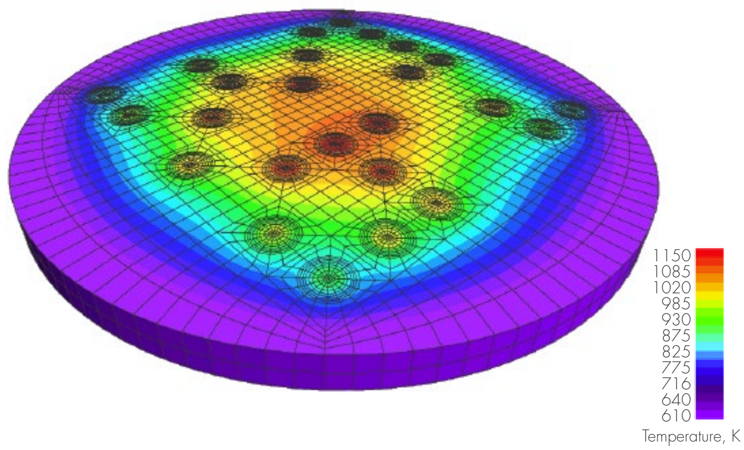

FIGURE 6. Temperature distribution in a cross-section of a 3D slab of a TRISO compact matrix model with a "sparse", random kernel distribution under prototypic gas-cooled reactor conditions. (Generated using the "spherical mesh object" tool.)

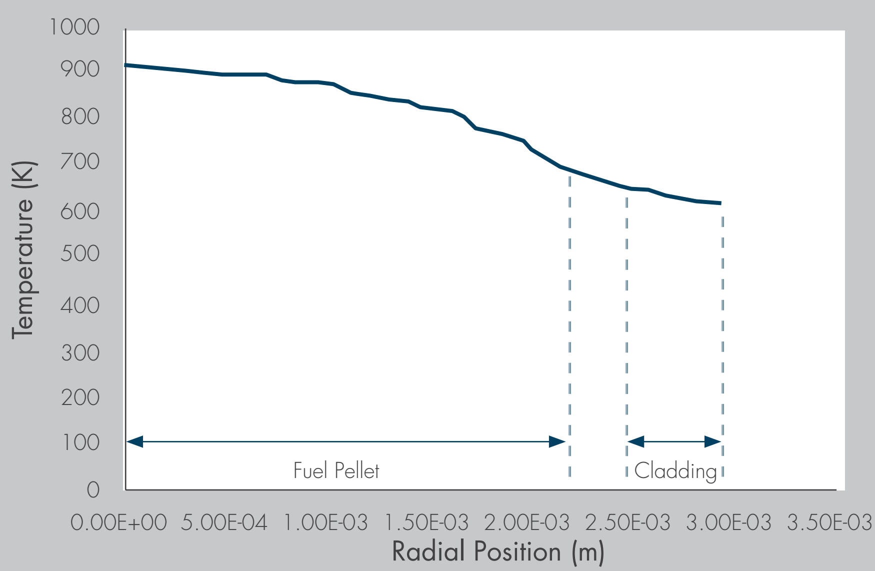

FIGURE 5. Radial Temperature Distribution Across the Fuel Rod Model at ~ 486 Days of Irradiation

of rod DP21, assembly X441 are shown in the figures above. Figure 4 provides a diagram of the computational model showing the primary components of the model and a plot of the temperature distribution throughout the fueled region of the rod at peak power. Figure 5 provides the radial temperature profile across the fuel rod from the center to the cladding outer surface at peak power near the end of the irradiation period. Temperatures vary from just ~900 K at the pellet center to ~650 K at the cladding surface. The temperature differential is fairly low at ~250 K, as would be expected from a high-conductivity metal fuel rod with a Na-bonded fuel cladding gap. These results are consistent with published experimental observations.

TRISO FUEL MODELING DEVELOPMENT

Several advanced fuel material models have been implemented specifically for TRISO fuel in PEGASUS, including thermal and mechanical models for UCO or UO2 kernels, PyC, SiC materials, and a fission gas release model for computing the release of gaseous fission products such as Xe and Kr. **In addition to the standard 3D and 2D axisymmetric modeling FEM capabilities in the code, PEGASUS contains several unique tools designed specifically to support TRISO fuel modeling and analysis.** These include a "spherical mesh object" tool that can automate the process of generating 2D/3D TRISO spheres, meshing them, and embedding them into a fuel matrix to allow modeling of individual TRISO kernels or fully encapsulated TRISO fuel forms. An example of models generated using the spherical mesh object tool is shown in Figure 6. The spherical mesh object capability is, to our knowledge, unique to PEGASUS and not found in any other fuel performance or general-purpose FEM code. PEGASUS also has a "reshape" function that can automate the process

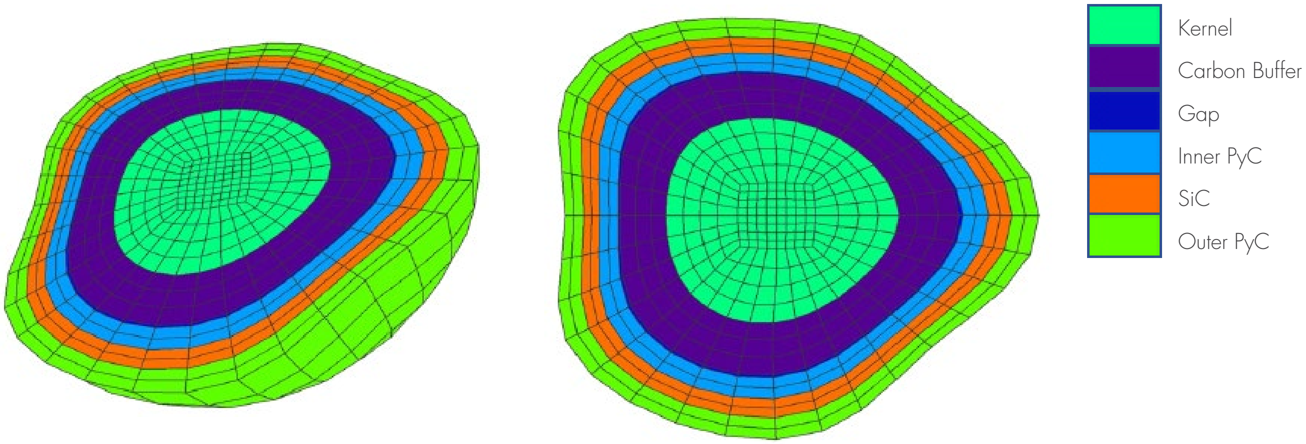

FIGURE 7. Deformed 3D TRISO particle meshes generated using the "reshape" function tool in PEGASUS.

of meshing and modeling deformed TRISO particles to increase user efficiency. Figure 7 illustrates particle meshes that were created using the reshape meshing tool.

These modeling capabilities allow PEGASUS to be used to investigate very detailed mechanical and structural effects in TRISO fuel forms. For example, enabling the detailed analysis of the mechanical interaction between TRISO fuel layers explicitly examining the effects of cracking, debonding, and asphericity within whole or damaged particles.

Planned future development work includes the integration of damage-mechanics modeling and fission product diffusion in the TRISO particle, fuel compact, ad matrix. One failure mode of particular interest that has been identified is cracking of the IPyC layer which propagates through the SiC outer layer. This can create a pathway for enhanced fission product release from the TRISO particle to the surrounding fuel matrix. This failure mechansim appears to occur when the buffer layer remains bonded to the IPyC layer providing the conditions for a synergistic mechanical and chemical failure mechanism that combines cracking, stress concentration, and chemical corrosion (localized Pd-induced corrosion in the SiC [6]. This failure mode is of interest because it can have a strong impact on fuel source term determination for operational TRISO fuel.

References

(1.) C. P. Deck et al., Overview of General Atomics SiGA™ SiC-SiC Composite Development for Accident Tolerant Fuel, Transactions of the American Nuclear Society, Vol. 120, Minneapolis, Minnesota, June 9–13, 2019.

(2.) J. Malone, A. Totemeier, N. Shapiro, and S. Vaidyanathan, Lightbridge Corporation's Advanced Metallic Fuel, Nuclear Technology, Vol 180, Dec. 2012.

(3.) Z. Huber and E. Conte, Casting and Characterization of U-50Zr, PNNL-33873, Pacific Northwest National Laboratory, Richland, Washington 99354, Jan. 2023.

(4.) C. E. Lahm, J. F. Koenig, R. G. Pahl, D. L. Porter, and D. C. Crawford, "Experience with Advanced Driver Fuels in EBR-II," J. Nucl. Mat. 204 (1993) 119-123.

(5.) G. L. Hofman, M. C. Billone, J. F. Koenig, J. M. Kramer, J. D. B. Lambert, L. Leibowitz, Y. Orechwa, D. R. Pedersen, D. L. Porter, H. Tsai, and A. E. Wright. Metallic fuels handbook, Technical Report ANL-NSE-3, Argonne National Laboratory, 2019.

(6.) J.D Hunn, C.A. Baldwin, T.J. Gerzak, F.C. Montgomery, R.N. Morris, C.M. Silva, P.A Demkowicz, J.M. Harp, and S.A. Ploger, Detection and Analysis of Particles with Failed SiC in AGR-1 Fuel Compacts, Nuclear Engineering and Design, April 2016.

SUMMARY

PEGASUS is an advanced analysis tool developed for industry applications that can provide a complimentary and independent capability for nuclear fuel performance. Recent development work on PEGASUS has focused on expanding the applicability of the code to the advanced fuel (ATF) and advanced reactor arena. Future development is planned for PEGASUS that will continue along multiple avenues with an emphasis on advanced fuels and specific thermo-mechanical issues within the industry, such as deterministic failure model development. One example of this is the aforementioned Pd-induced failure mechanism identified for TRISO fuel. SI is actively seeking partners within the advanced fuel community to collaborate with on this work and would welcome inquiries and proposals for expanded application of PEGASUS.

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

in Pressurized Water Reactor (PWR) Coolant Systems

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The CASS piping welds present in many PWR plants provide numerous and complicated challenges to their effective ultrasonic examinations. To this point, a viable ultrasonic examination solution for the inspection of these piping components, as required by ASME Code Section IX, had previously not been available. By leveraging our technical expertise in materials, technology development, and advanced NDE deployment, Structural Integrity Associates, Inc (SI) has developed a new system that will provide a meaningful solution for the examination of CASS piping components. The result of this program will be the first commercial offering for the volumetric examination of CASS components in the nuclear industry.

BACKGROUND INFORMATION

ASME Section XI Class 1 RCS piping system welds fabricated using CASS materials pose serious and well-understood challenges to their effective ultrasonic examination. For decades, utilities and regulators have struggled with the administrative and financial burdens of Relief Requests, which were, and still are, based on the inability to perform meaningful volumetric examinations of welds in CASS components.

> Many years of futility and frustration may have fostered the belief that technology allowing effective and meaningful examination of CASS materials would never be achievable. This is no longer the case.

The failure mechanism for CASS material occurs through the loss of fracture toughness due to thermal aging embrittlement. The susceptibility of CASS material to thermal aging embrittlement is strongly affected by several factors, primary of which are system operating time and temperature, the casting method used during component manufacture, and molybdenum and ferrite content. In addition to the existing ASME Section XI requirements for the examination of welds in CASS materials, the susceptibility to thermal aging embrittlement drives the requirement for additional examinations (including ultrasonic examinations) as directed by several NRC-published NUREGs required for plant license renewal. The existence of a viable, effective examination capability for CASS materials plays a very important part in both currently required Inservice Inspections (ISI) and plant license renewal.

CASS MATERIAL PROPERTIES AND EFFECT ON ULTRASONIC EXAMINATION

Metallurgical studies have revealed that the microstructure of CASS piping can vary drastically in the radial (through-wall) direction, as well as around the circumference and along the length of any given piping segment. Large and small equiaxed, columnar and mixed (combinations of equiaxed and columnar grains), and banding (layers of substantially different grain structures) are commonly observed in CASS piping materials. None of these conditions favor the performance of effective ultrasonic examinations.

The very large and widely varying types (equiaxed, columnar, and randomly mixed), sizes and orientations of the anisotropic grains in CASS material are very problematic. Anisotropic is defined as an object or substance having a physical property that has a different value when measured in different directions. Such physical properties strongly affect the propagation of ultrasound in CASS material by causing severe attenuation (loss of energy through beam scattering and absorption), beam redirection, and unpredictable changes in ultrasonic wave velocity. These factors are responsible for the inability of ultrasonic examination to completely and reliably interrogate the Code-required volume (inner 1/3 T_{nom}) of welds in CASS piping material. Interestingly, CASS materials less than 1.6" T_{nom} (Pressurizer Surge Piping) can be effectively examined, while CASS materials over 2.00" (Main RCS Coolant Loop Piping) are less effectively examined. Consequently, an ASME Section XI, Appendix VIII qualification program for CASS piping components has not been established and remains in the course of preparation. Nonetheless, ASME Section XI requirements to conduct inservice examinations of RCS piping welds fabricated from CASS components remain fully in force.

FIGURE 1. An example of the widely-varying microstructure of a centrifugally cast piping segment. False-color imaging is used to aid visualizing grain variations. (Image from NUREG/CR-6933 PNNL-16292)

ASME CODE ACTIONS AFFECTING CASS PIPING EXAMINATIONS

ASME Section XI Code Case N-824, "Ultrasonic Examination of Cast Austenitic Piping Welds From the Outside Surface," was approved by ASME in October 2012 and by the NRC in October 2019. This Code Case provides the first approved direction for the ultrasonic examination of welds joining CASS piping components. The ASME B&PV Code, Section XI, 2015 Edition, incorporates Code Case N 824 into Mandatory Appendix III in the form of Mandatory Supplement 2. To date, these two ASME Section XI Code documents remain the **sole sources** approved by ASME and NRC that provide specific direction for the examination of CASS RCS piping system welds and, therefore, form the foundation of SI's approach for the development of our CASS ultrasonic examination solution.

SI'S CASS PROGRAM DESCRIPTION

SI is developing the industry's most well-conceived and capable ultrasonic system for the examination of welds in CASS piping components. To accomplish this objective, SI has drawn upon our internal knowledge and experience, supplemented by a careful study of numerous authoritative bodies of knowledge relating to the examination of CASS components. The development of the SI examination system has been guided by both SI's industry-leading 17 years of experience conducting phased array examinations in nuclear power plants and the knowledge acquired through the careful study of the topical information contained within industry-recognized publications. These published results of extensive industry research provided both guidance for the selection of phased array system components and CASS-specific material insights that strengthen the technical content of our Appendix III-based procedure.

CASS PROGRAM ELEMENTS

SI believes that the procedure, equipment and personnel featured in this program will be equivalent or superior to those that will form the industry-consensus approach for CASS ultrasonic examinations needed to successfully achieve Appendix VIII, (future) Supplement 9, "Qualification Requirements for Cast Austenitic Piping Welds."

Ultrasonic Procedure - SI has crafted an ultrasonic examination procedure framework that is fully compliant with ASME Section XI, Mandatory Appendix III, Supplement 2, along with referenced Section XI Appendices as modified by the applicable regulatory documents.

Ultrasonic Equipment - SI has acquired and assembled the ultrasonic system components required by Code Case N-824 and Appendix III,

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Supplement 2, which includes the following:

- Ultrasonic instrumentation capable of functioning over the entire expected range of examination frequencies. The standard examination frequency range extends from low-frequency, 500 KHz operation for RCS main loop piping welds through 1.0 MHz for pressurizer surge piping.

SI has designed and acquired additional phased array transducers that meet the physical requirements of frequency, wave mode, and aperture size and are capable of generating the prescribed examination angles with the required focal properties. SI has designed and fabricated an assortment of wedge assemblies that will be mated with our phased array probes to provide effective sound field coupling to the CASS components being examined. SI's wedge designs consider the CASS pipe outside diameter and thickness dimensions and employ natural wedge-to-material refraction to assure optimal energy transmission and sound field focusing.

SI also possesses several data encoding options that are necessary to acquire ultrasonic data over the expected range of component access and surface conditions. The encoding options will include:

- Fully-automated scanning system, capable of driving the relatively large and heavy 500KHz phased array probes
- The SI-developed Latitude manually-driven encoding system, which has been deployed during PDI-qualified dissimilar metal DM weld examinations in nuclear power plants

Examination Personnel - SI's ultrasonic examination personnel are thoroughly trained and experienced in all elements of encoded ultrasonic data acquisition and analysis in nuclear plants. SI's examiners have a minimum of 10 years of experience and hold multiple PDI qualifications in manual and encoded techniques. SI recognizes the challenges that exist with the examination of CASS piping welds and has developed a comprehensive program of specialized, mandatory training for personnel involved with CASS examinations. This training includes descriptions of coarse grain structures, their effect on the ultrasonic beam, and the expected ultrasonic response characteristics of metallurgical and flaw reflectors, as well as the evaluation of CASS component surface conditions.

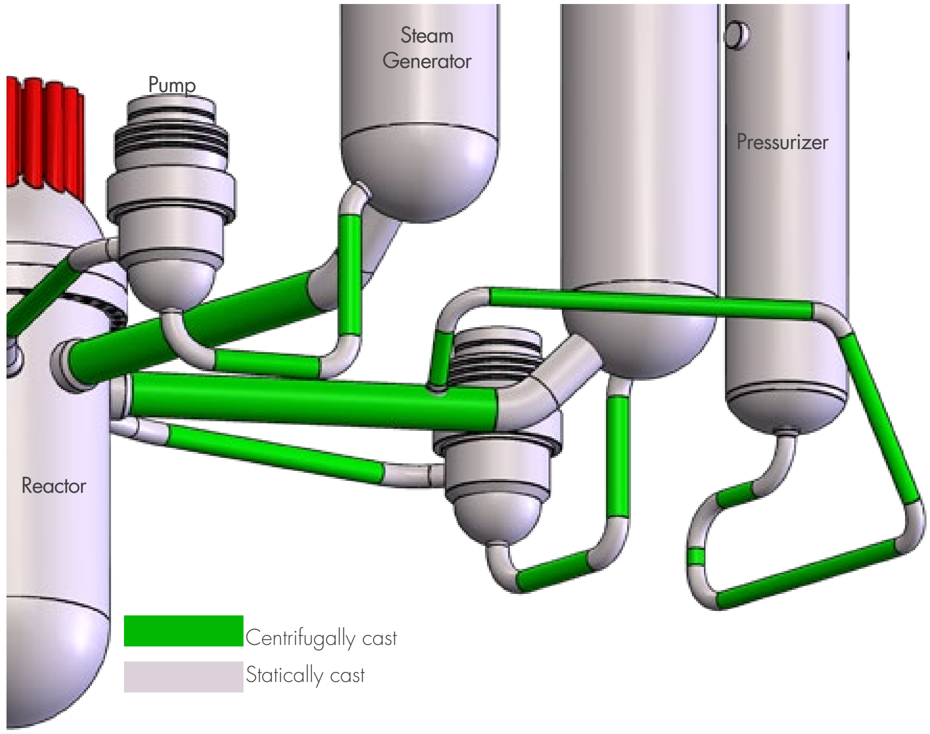


FIGURE 2. PWR RCS Major Components

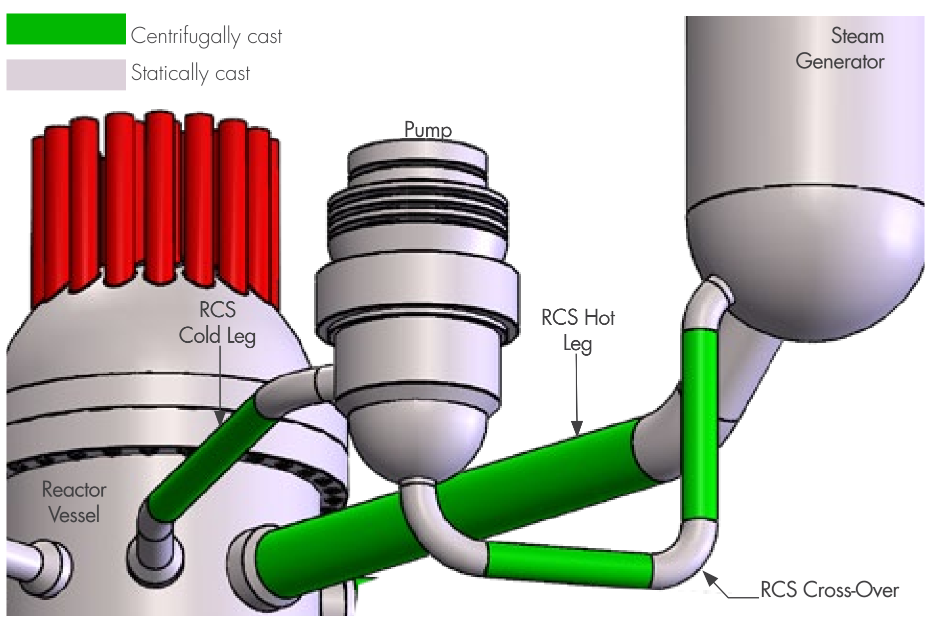


FIGURE 3. RCS Coolant Pump and Crossover Piping

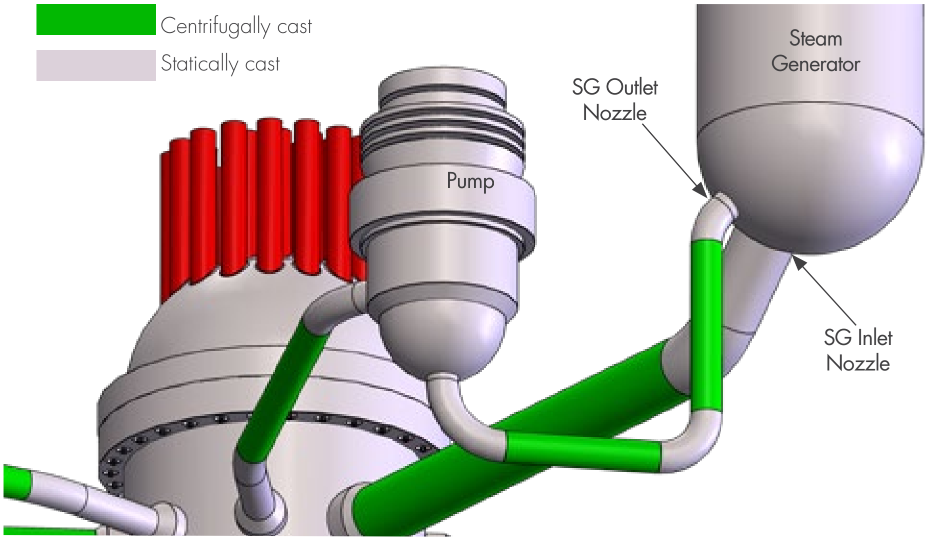


FIGURE 4. Steam Generator Details

ULTRASONIC TECHNIQUE VALIDATION

Although not required by the ASME Code, SI has arranged for access to CASS piping system specimens from reputable sources to validate the efficiency of our data acquisition process and the performance of our ultrasonic examination techniques. The specimens represent various pipe sizes and wall thicknesses and contain flaws of known location and size to permit the validation and optimization of SI's data acquisition and analysis processes. SI will thoroughly analyze, document, and publish the results of our system performance during the examination of the subject CASS specimens.

CASS PIPING SYSTEM APPLICATIONS

Typical CASS Piping Weld Locations in PWR Reactor Coolant Systems
The following graphic illustrates the location and extent of CASS materials in the RCS of many PWR plants.

RCS Main Loop Piping Welds: This portion of the RCS contains large diameter butt welds that join centrifugally cast stainless steel (CCSS) piping segments to statically cast stainless steel (SCSS) elbows and reactor coolant pump (RCP) casings. RCS main loop piping includes the following subassemblies:

- Hot leg piping from the Reactor Vessel Outlet to the SG Inlet
- Cross-over piping from the SG Outlet to the RCP Inlet
- Cold leg piping from the RCP Outlet to the RPV Inlet

Steam Generator Inlet / Outlet Nozzle DM Welds: These terminal end DM butt welds are present in PWR plants, both with and without safe ends between the SCSS elbows and the ferritic steel nozzle forgings.

Pressurizer Surge Piping Welds: This portion of the RCS contains a series of butt welds fabricated using CCSS piping segments to SCSS elbows between the Pressurizer Surge nozzle end and the Hot Leg Surge nozzle.

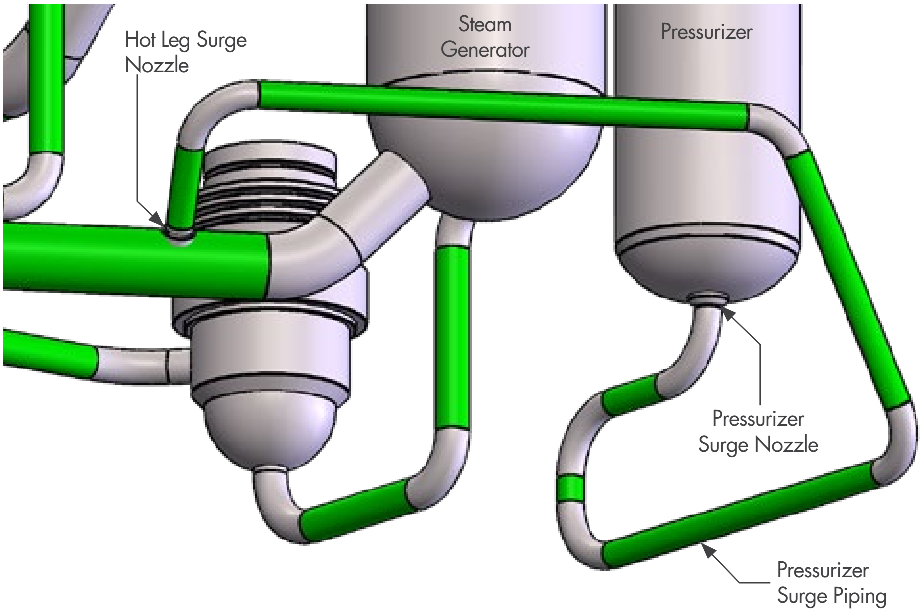


FIGURE 5. Pressurizer and Surge Line Details

SUMMARY

The CASS piping welds present in many PWR plants provide numerous and complicated challenges to their effective ultrasonic examinations. SI's new CASS ultrasonic examination system will provide a new and meaningful solution.

PROJECT TIMELINE

SI is working to complete the development, integration and capability demonstrations of the CASS ultrasonic examination system described in this document for limited (emergent) fall 2023 and scheduled deployments beginning in spring 2024.

Operational Chemistry

Training (BWRs and PWRs)

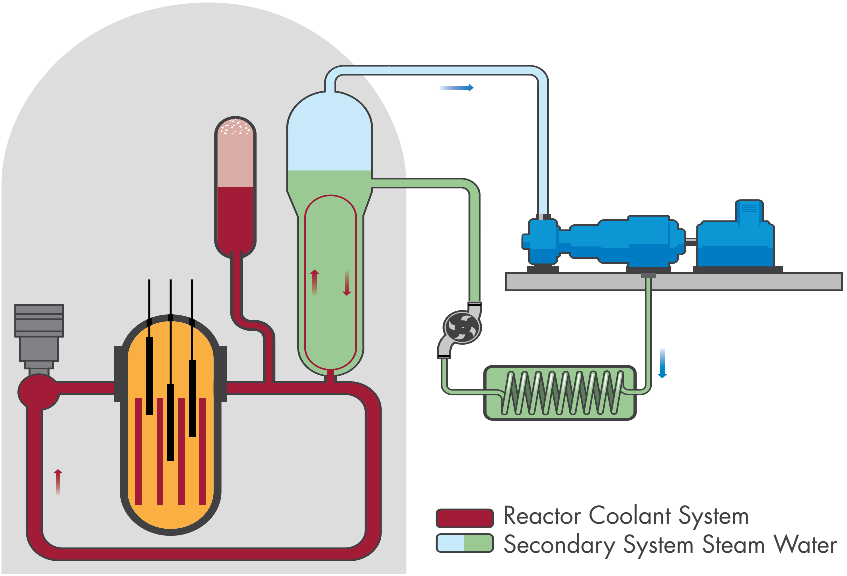
Structural Integrity's chemistry training programs feature courses led by industry-recognized technical experts to support knowledge transfer and retention of your workforce.

OVERVIEW

These courses provide practical, hands-on information and techniques for personnel responsible for operational chemistry analysis, corrosion prevention, and system diagnostics. Attendees are encouraged to bring plant data for group discussion and analysis. BWR and PWR systems are covered as well as primary and secondary chemistry, radiochemistry, balance of plant chemistry, demineralizer and filtration performance, start up and shutdown chemistry, corrosion concerns, and data evaluation techniques.

WHO SHOULD ATTEND

Chemists and Engineers who require practical knowledge of Boiling Water or Pressurized Water Reactors operational water chemistry. These courses are designed for chemistry personnel that have a basic understanding of plant operation and plant systems, focusing on the essentials of primary and secondary chemistry and processing equipment used in BWR or PWR water chemistry operations.



BWR OPERATIONAL CHEMISTRY

EVENT DATE
September 18-22, 2023

LOCATION/HOSTED BY
Dresden Nuclear Power Plant

REGISTRATION
www.structint.com/bwr-operational-chemistry

PWR OPERATIONAL CHEMISTRY

EVENT DATE
September 18-22, 2023

LOCATION
Structural Integrity Associates, Inc.
Huntersville, NC Office

REGISTRATION
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An ECA Process for the Impact of Hydrogen Blending on Girth Weld Defects

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Several pipeline operators have established pilot demonstration programs to blend hydrogen with natural gas (hydrogen blending) in their gas transmission pipelines. Structural Integrity Associates (SI) has been providing clients technical consulting support to complete engineering critical assessment (ECA) projects to help evaluate the potential impact to pipeline integrity and help ensure the safety of the public, customers, employees, and the natural gas pipeline infrastructure.

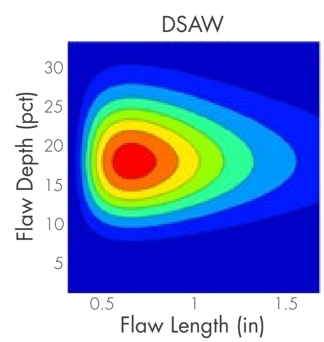
In a recent study, girth weld defects were identified as a key threat to pipeline integrity, particularly when the pipeline is exposed to large axial strain due to soil movement (which can be experienced from landslides, underwater erosion, storm surge, ground settlement and lateral spreading). The impact to girth weld defects combined with large strain can pose a significant threat that is further exacerbated with hydrogen blending. SI developed and implemented a program to complete a detailed ECA using probabilistic risk modeling to assess the probability of rupture (POR) to an offshore pipeline that had experienced significant strain due to erosion of the channel area, pipeline movement, and sand waves in the sea channel.

To complete the ECA, a probabilistic analysis was performed consisting of the following activities:

REVIEW OF IN-LINE INSPECTION RESULTS

- Recent strain data collected from an Inertial Mapping Unit (IMU) In-Line Inspection (ILI) tool were reviewed and analyzed to create a map of applicable strain at each girth weld in the study.

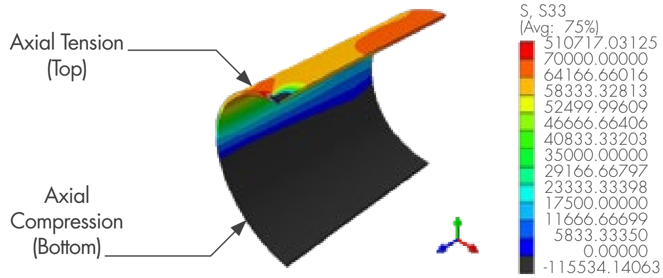
MATERIAL PROPERTY, DEFECT AND OPERATING DATA ANALYSIS

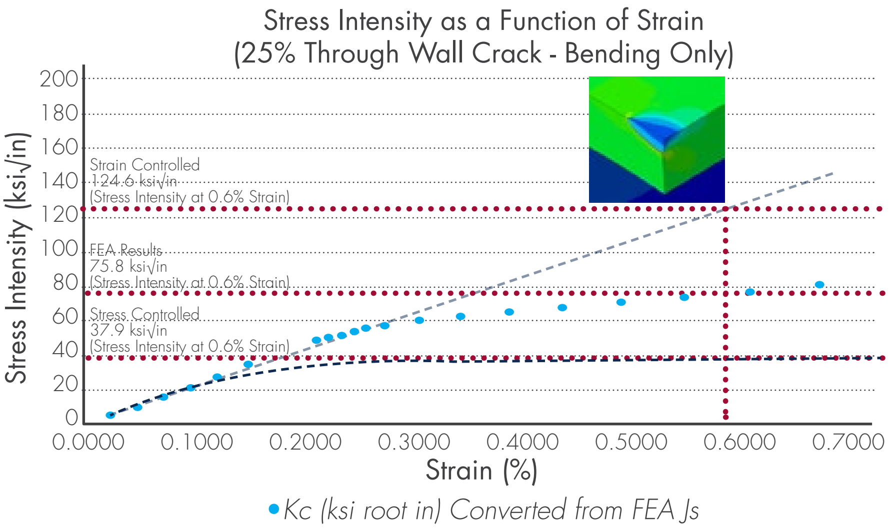


- Pipe populations were developed with specific characteristics that make them more compatible with hydrogen blending, or less compatible due to the respective susceptibility to hydrogen-related threats under different operating conditions.
- SI developed Statistical distributions for key material properties (strength, toughness, wall thickness, etc.) and girth weld defect characteristics (length, depth, etc) using client specific and industry databases.
- SI reviewed and incorporated relevant material tests performed to evaluate the effects of targeted hydrogen blend levels on the materials of interest (carbon steel base metal, longitudinal seam welds and girth welds).

DETERMINISTIC ANALYSIS USING FINITE ELEMENT MODELING (FEM)

- A finite element analysis was utilized to determine the stress intensity factor of a circumferentially oriented crack subjected to high bending loads resulting in large axial strain. The elastic-plastic analysis was used to determine the stress intensity factor as a function of strain, for a circumferentially oriented, externally breaking crack subject to a bending stress.





DEVELOPMENT OF A FRACTURE MECHANICS MODEL (FOR PROBABILISTIC MODELING)

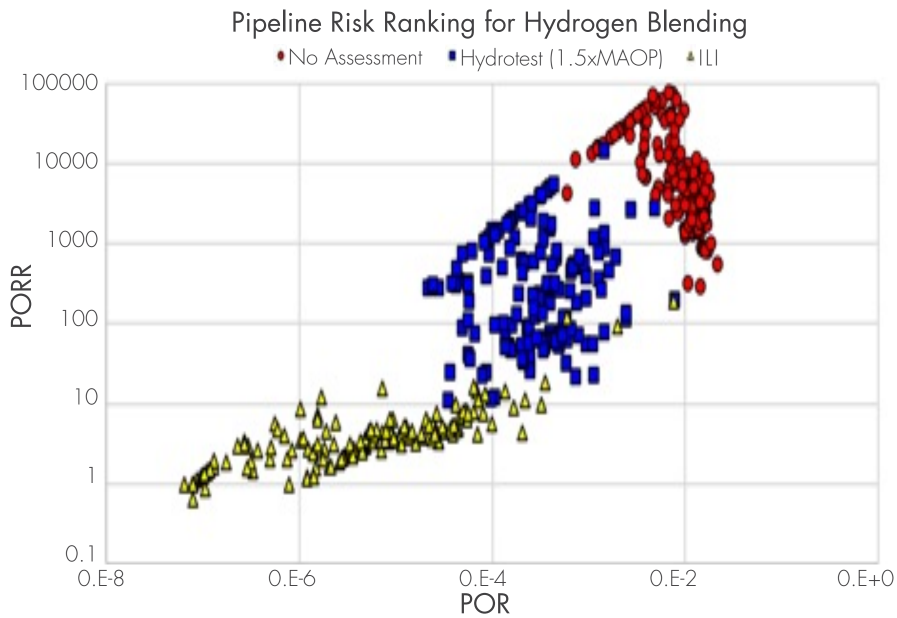
- From the FEA results a simplified elastic model was developed relating the stress intensity factor to the peak tensile axial strain resulting from bending.
- SI incorporated the stress intensity factor from this model into an API 579 FAD based evaluation of girth weld, crack-like defects.

REVISIONS TO SI SYNTHESIS™ SOFTWARE

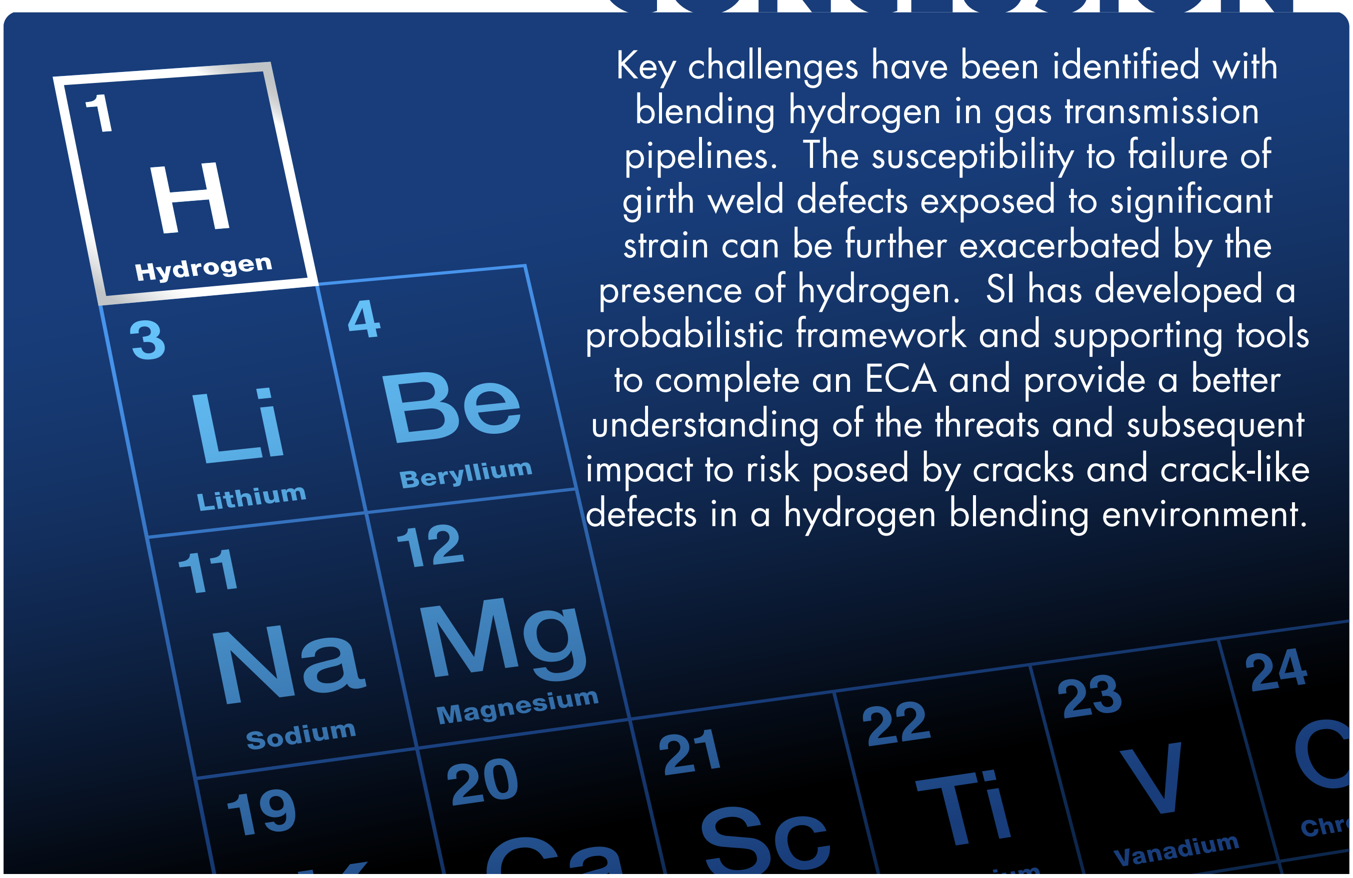
- SI has developed specialized risk analysis software tools to evaluate pipeline POR which were applied to evaluate the impact or hydrogen blending to the POR.
- The software was specifically enhanced for this analysis to incorporate the following items:
  - Evaluation of flaws associated with circumferential cracking (such as those that may be encountered in vintage girth welds).
  - Incorporation of secondary loads and stresses (such as those encountered through land/soil movement).

PROBABILISTIC ANALYSIS

- SI applied the probabilistic framework to evaluate the increased susceptibility to failure imposed from hydrogen blending with special consideration for ground movement and girth weld defects.
- This framework used Probabilistic Fracture Mechanics (PFM) and addressed the following phenomena associated with hydrogen blending:
  - Accelerated crack growth rates and
  - Hydrogen embrittlement of the pipeline steel.
- The POR was then evaluated for each active threat on the pipeline, comparing the risks associated with pure natural gas service to natural gas with hydrogen blending, considering various assessment options (hydrotest or ILI) prior to hydrogen injection.



CONCLUSION



Key challenges have been identified with blending hydrogen in gas transmission pipelines. The susceptibility to failure of girth weld defects exposed to significant strain can be further exacerbated by the presence of hydrogen. SI has developed a probabilistic framework and supporting tools to complete an ECA and provide a better understanding of the threats and subsequent impact to risk posed by cracks and crack-like defects in a hydrogen blending environment.

Gas Pipeline Safety Regulation Update

RIN1, RIN2, and the Valve Rule

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Structural Integrity (SI) has significant depth and expertise in pipeline safety regulations and dedicates substantial resources to ensure a comprehensive understanding of proposed and newly enacted pipeline regulations.

> Using the most current insights relative to regulations, SI frequently consults with clients in helping to implement strategic direction that will best position their pipeline safety programs to comply with the new regulations effectively.

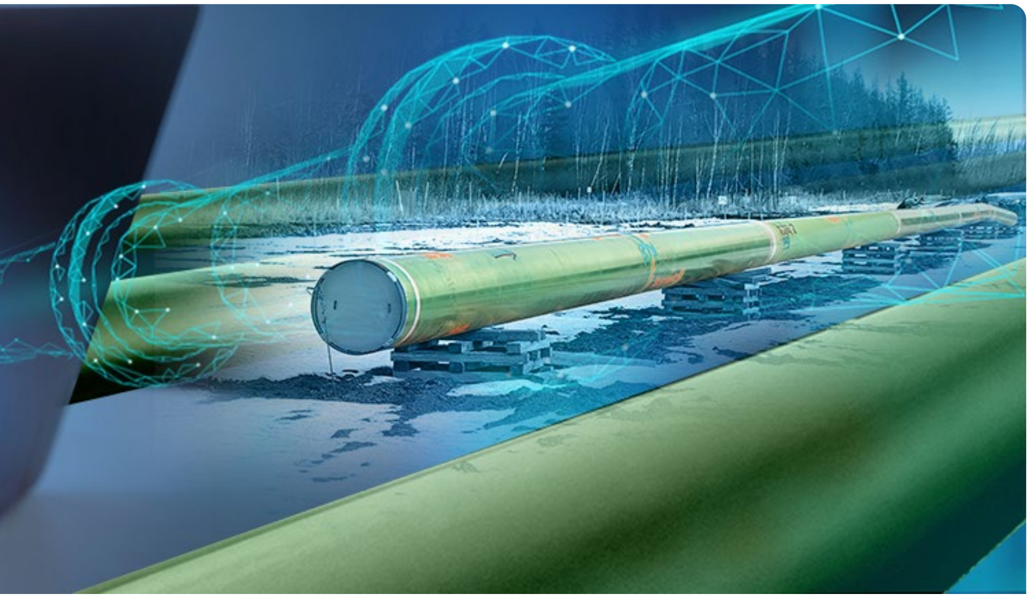
The following shows how SI currently provides regulatory consulting support to clients for RIN 1, RIN 2, and the Valve Rule.

REGULATORY OVERVIEW: GAS TRANSMISSION SAFETY RULE (GTSR) RIN 1

On October 1, 2019, the Pipeline and Hazardous Materials Safety Administration (PHMSA) published amendments to 49 Code of Federal Regulations (CFR), Parts 191 and 192 in the Federal Register, issuing Part 1 or Rulemaking Identification Number (RIN 1) of the Gas Transmission Safety Rule. This new regulation represents the most significant regulatory impact on gas transmission pipelines since the original pipeline safety regulations were issued in 1970.

RIN 1 incorporates numerous prescriptive actions required for gas transmission pipeline operators to improve pipeline safety:

- MAOP Determination and Reconfirmation (§192.619 and §192.624)
- Material Verification (MV) (§192.607)
- Engineering Critical Assessments (ECAs) (§192.632)
- The identification and assessment of Moderate Consequence Areas (MCAs) (§192.3 & §192.710)
- Analysis of Predicted Failure Pressure (§192.712)
- Revisions to Transmission Integrity Management Program (TIMP) Plans, required new Plans, procedures, and record requirements.



HOW SI IS PROVIDING SUPPORT:

SI has developed specific Plans, procedures, applications, and expertise to assist operators in addressing the requirements of RIN 1, including the following:

- Updated TIMP Plans
- New Transmission Pipeline Assessment Plans Outside High Consequence Areas
- MAOP Reconfirmation Plans
- Implementation Support of MAOP Reconfirmation Projects (e.g., Pressure Testing, Engineering Critical Assessment Projects)
- Material Verification (MV) Procedures
- MVI™ , a database application for managing and monitoring progress through the Material Verification (MV) process.
- MV Field Support.
- ECA Procedures and Implementation.
- APTITUDE, a software application for evaluating the predicted failure pressure of crack and crack-like defects.

Continued on next page

REGULATORY OVERVIEW: GAS TRANSMISSION SAFETY RULE (GTSR) RIN 2:

On October 24, 2022, PHMSA released RIN 2 of the Gas Transmission Safety Rule. **RIN 2 includes comprehensive changes to the Federal Pipeline Safety Regulations pertaining to gas transmission pipelines, including:**

- Revisions to the definition of a Transmission Line,
- Inspection and repair criteria for newly constructed pipelines,
- New external corrosion monitoring, testing, and remediation requirements,
- New internal corrosion monitoring and remediation requirements,
- New Predicted Failure Pressure and Engineering Critical Assessment requirements for Dents and Mechanical Damage,
- Revised repair criteria for High Consequence Areas (HCAs),
- New repair criteria for transmission pipelines outside HCAs,
- Enhanced data gathering and integration requirements for threat assessment,
- Updated Direct Assessment requirements.

SI IS CURRENTLY WORKING WITH CLIENTS TO SUPPORT THE FOLLOWING ACTIVITIES

- Revising TIMP Plans and Transmission Pipeline Assessment Plans Outside High Consequence Areas for RIN 2 requirements.
- Development of new PFP Procedures and Tools to address the requirements for Dents and Mechanical Damage,
- Developing and implementing internal corrosion monitoring programs,
- Developing and revising O&M Procedures and/or Gas Engineering Standards to address new transmission pipeline repair requirements.
- Revising SCC Direct Assessment and Internal Corrosion Direct Assessment procedures.
- Reviewing and recommending improvements on threat identification, evaluation, and risk ranking methodologies in the context of the new requirements defined in §192.917.

REGULATORY OVERVIEW: VALVE RULE

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

On April 8, 2022, PHMSA issued a new regulation, "Requirement of Valve Installation and Minimum Rupture Detection Standards" (Valve Rule). The Valve Rule prescribes new requirements for the installation of rupture mitigation valves (RMVs) on new and replaced transmission pipelines. In addition, the Rule prescribes new requirements for detection and response to a potential pipeline rupture.

SI has developed specific procedures and programs to support operators in addressing the Valve Rule, including the following:

- Risk Analysis of the need for RMVs on transmission pipeline systems.
- Review and update of existing procedures impacted by the Valve Rule requirements, including emergency response, locations required for valve installation, operations, and maintenance.
- Develop new, comprehensive procedures and processes to support operator compliance, including defining Gas Control Room identification and responses to potential ruptures, significant gas releases, and confirmed ruptures.

NOTICE

Starting August 1, 2023, Structural Integrity's Oil and Gas Business Unit will be rebranded as Pipeline Integrity Compliance Solutions (PICS) to better align with our core market and the services we provide to the pipeline industry.

Serviceability Assessment of an L-Grade Stainless Steel Pipe Fitting

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A client recently ordered a Type 316 stainless steel pipe coupling fitting for use in a high-pressure, high-temperature steam line operating at 1005°F. The fitting that was received was so-called dual grade Type 316/316L stainless steel. Given the limitations on using "L" grades of stainless steel at high temperatures, the client requested that SI perform a serviceability assessment for the fitting to determine if it could be safely used until the next scheduled outage when a replacement non-L grade fitting would be available.

BACKGROUND

The fitting ordered was a ½" nominal diameter (NPS ½), 6000# (Class 6000) full coupling socket-welding fitting in accordance with the ASME B16.11 specification, material ASME SA-182 forging, Type 316 stainless steel (designated as F316 in SA-182). The fitting supplied was dual grade F316/316L material with a carbon content of 0.023% per the material

Continued on next page

test certificate. The designation of this material as "dual grade" means that it meets the requirements of both F316 and F316L material grades. This is possible because the chemical composition requirements of these two grades overlap, with the primary difference between them being carbon content. For F316 the carbon content is specified to be 0.08% maximum (no minimum), while for F316L the carbon content is specified to be 0.030% maximum. Therefore, material with carbon content less than 0.030% will meet the requirements for both grades. It is worth noting that the carbon content of "H" grade of 316 stainless steel (F316H per SA-182) is specified to be 0.04-0.10%. The H grade is intended for use at high temperatures.

The received fitting was installed in a main steam valve pressure equalizing line with a steam temperature/pressure of 2750 psia/1015°F at design conditions and 2520 psia/1005°F at operating conditions. The fitting was welded to Grade P11 pipe on one side and Grade P22 pipe on the other side. The applicable code was stated to be ASME BPVC Section I.

With a reported carbon content of less than 0.04%, the fitting is technically not permitted for use in ASME Section I construction above a temperature of 1000°F. Per the ASME Boiler and Pressure Vessel Code (BPVC) Section II, Part D, Table 1A, the allowable stresses for SA-182, F316 material are valid at or above 1000°F only when the carbon content is greater than 0.04% (Note G12). Per the same table, SA-182, F316L material is only permitted for use in Section I construction up to 850°F. The reason for this temperature limitation is that the long-term creep-rupture strength of Type 316 stainless steel with lower carbon content is reduced compared to material with higher carbon content because fewer carbides form during service to strengthen the grain boundaries. There are no other adverse impacts of the lower carbon content, e.g., on fatigue strength or oxidation resistance.

The short-term serviceability of the fitting with low carbon content was assessed by comparing bounding pressure stresses in the fitting with the reported creep-rupture strength for Type 316L material. Per the ASME B16.11 specification, Class 6000 socket-welding fittings are compatible with NPS Schedule 160 pipe, meaning that pressure stresses in the fitting will be less than those in Sch 160 pipe with minimum wall thickness according to ASME B36.10 (pipe dimension specification), in other words, the fitting will be at least as strong as the pipe.

ASSESSMENT

The dimensions of NPS ½, Schedule 160 pipe per the ASME B36.10 pipe specification are 0.84" outer diameter (OD), 0.165" minimum wall thickness (MWT). For an operating steam pressure of 2,520 psi, the reference hoop stress per the equation in ASME BPVC Section I, Appendix A-317 is 5.05 ksi. Per the general design guidance in ASME B16.11 (Section 2.1.1) the pressure stresses in the fitting must be less than this. Since the fitting in question is cylindrical, comparative hoop stresses can also be calculated from dimensions given in ASME B16.11, although these may not be exact due to the varied wall thickness in the fitting. According to Table I-1 of ASME B16.11, the central body of the fitting is 1.283" OD and 0.395"

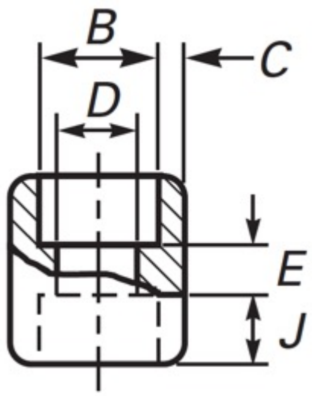

FIGURE 1. Schematic diagram for a socket-welding coupling fitting. Per ASME B16.11, an NPS ½, Class 6000 fitting has relevant dimensions B = 0.875″ maximum, C = 0.204″ minimum, and D = 0.434″ minimum.

MWT (Figure 1). The reference hoop stress calculated using the A-317 equation at 2,520 psi stream pressure and these dimensions is 2.63 ksi, considerably less than 5.05 ksi. In the female socket ends of the fitting, the OD is also 1.283", but the minimum wall thickness is 0.204", leading to a calculated reference hoop pressure stress of 6.58 ksi. Note that the actual stresses in the socket ends will be much less than this because the pipe will be inserted and welded into the socket, taking up the pressure loading, but the calculated stress can be taken as a bounding value.

Creep-rupture strengths for Type 316L stainless steel have been reported in ASTM Data Series DS 5S2 publication, "An Evaluation of the Yield, Tensile, Creep, and Rupture Strengths of Wrought 304, 316, 321, and 347 Stainless Steels at Elevated Temperatures" (ASTM, 1969). According to Table 7 in this report, the average 10,000 hour creep-rupture strengths for Type 316L at 1000°F and 1050°F are 34.5 and 25 ksi, respectively. Minimum creep-rupture strengths are typically taken as 80% of the average strength, so the inferred minimum strengths at 1000°F and 1050°F are 27.6 and 20 ksi, respectively.

The reported 10,000 hour creep-rupture strengths in the temperature range of interest are more than twice the calculated bounding pressure stresses in the fitting, so it was judged that there is very little risk of failure of the fitting by creep-rupture in the next 10,000 hours of service.

This result is unsurprising since the 1005°F is barely into the creep range for Type 316 regardless of carbon content. The carbon content effects become more pronounced at higher temperatures (approximately 1100°F and above).

CONCLUSION

Based on the above assessment, it was SI's opinion that the Type 316L fitting with carbon content less than 0.03% was suitable for a limited period of service (less than 10,000 hours) until it can be replaced. Given that the fitting is reportedly welded to low-alloy steel pipe on either side, SI also recommended that a Grade 22 (2.25Cr-1Mo) low-alloy steel fitting be considered as a replacement, which would eliminate dissimilar metal welds (DMWs) between the fitting and pipes. DMWs are prone to premature failure due to thermal fatigue, weld fusion line cracking, and decarburization of the ferritic material. This voluntary recommendation made by SI, was not part of the original scope of work, but may have been just as critical a finding as it shed light upon a failure risk previously unknown by the client.

Materials Lab Featured Damage Mechanism

Circumferential Thermal Fatigue in Conventional Waterwall Tubes

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Circumferential Thermal Fatigue damage in Conventional Waterwall Tubes most commonly appears as circumferentially oriented cracking in the waterwalls of coal-fired supercritical units. Initially, the formation of ripple magnetite was a significant factor in the formation of this damage. Later, the introduction of oxygenated treatment controlled the formation of ripple magnetite, thus greatly reducing this damage mechanism. In the early 2000s, however, this type of thermal fatigue began occurring more frequently as low NOx burners and separated overfire air systems were introduced.

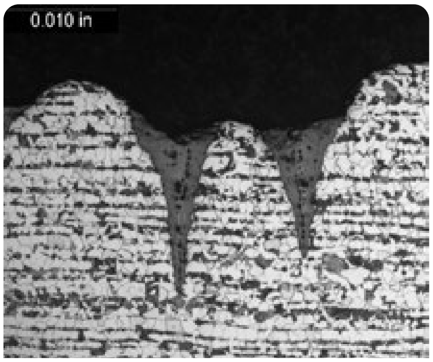
FIGURE 1. Tube with a series of circumferential cracks

MECHANISM

Three basic factors contribute to this type of thermal fatigue damage.

1. The first factor is the starting tube temperature (i.e., the temperature under normal operating conditions). The higher the starting temperature, the greater the accumulation of damage in the affected tubing. For example, tubes subjected to higher heat flux or tubes with thick weld overlays will have higher average metal temperatures and accumulate damage more quickly.
2. The second factor is the extent of gradually increasing tube temperature caused by reasons such as internal deposit buildup, flame impingement, or unstable flow.
3. The third factor is the contribution of thermal transients due to slag shedding or using sootblowers or water cannons.

Essentially, the thermal fatigue cracking results from the combination of increasing tube metal temperature and thermal transients and is aggravated by high starting tube temperatures.



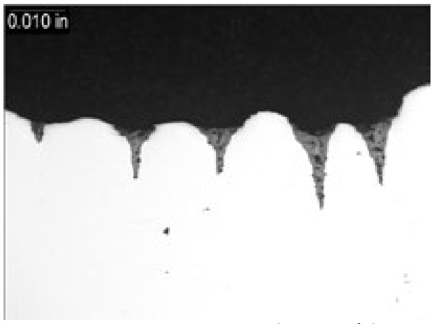


FIGURE 3. Cross-sectional views of the cracking in the etched (TOP) and unetched (BOTTOM) conditions

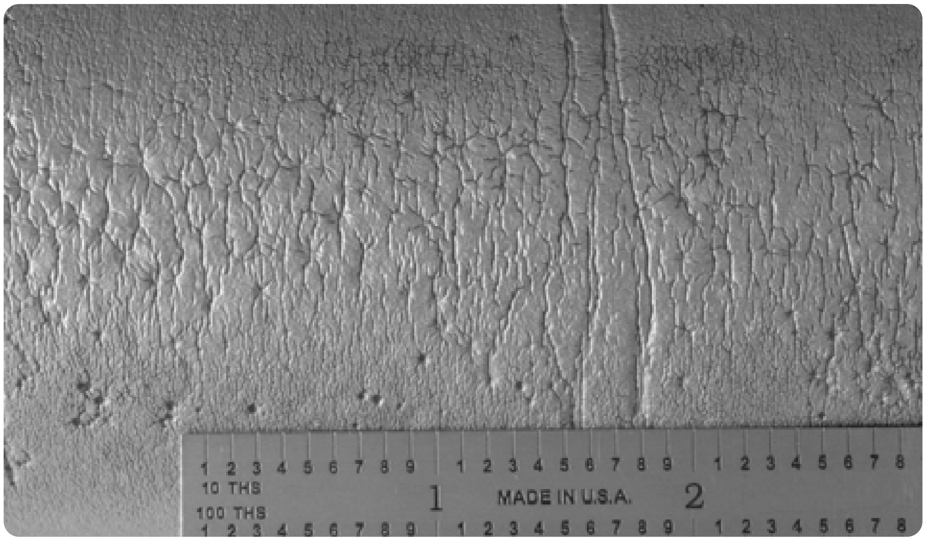


FIGURE 2. The external surface of the tube after the external deposits were removed

TYPICAL LOCATIONS

- Tubes with slag buildup and shedding
- Areas affected by wall blow quenching
- High heat flux locations
- Areas affected by flame impingement
- Cracking can be localized or widespread
- Tends to be contained within a relatively narrow range of elevations

FEATURES

- Circumferentially oriented, multiple, parallel cracks along the hot side of the tubes.
- Notch shaped, oxide filled cracks in cross-section.
- Adjacent tubes can exhibit variability in crack density.

ROOT CAUSES

- High Initial Waterwall Tube Temperatures
  - Thick weld overlays
  - Higher heat flux
  - Flame impingement

- Increasing Waterwall Tube Temperatures
  - Internal deposits including ripple magnetite, thick oxide layers, or feedwater corrosion products
  - Reduced internal flow rate
  - Formation of external oxides and deposits

- Severe Thermal Transients
  - Natural or forced slag removal, including slag shedding and sootblowing
  - Use of water cannons or improper sootblowing
  - Flame instabilities
  - Unit operation, including forced fan cooling, rapid startups, frequent load cycling

Phased Array Ultrasonic Testing (PAUT) Monitoring with Ultrasonic Thick-Film Arrays

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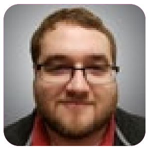

Traditional nondestructive examination (NDE) activities are planned based on hours of service, number of load cycles, time elapsed since previous inspections, or after the emergence of clear and obvious damage in a component. While engineering judgment and risk analysis can, and should, be used to prioritize inspections, these prioritizations are not based on the actual physical condition of the component or material it is constructed from but on precursory conditions that may or may not lead to eventual damage. Alternatively, continuous monitoring approaches can facilitate advanced planning and the optimization of Operations and Maintenance (O&M) spending by enabling the prioritization of inspections based on a component's actual current condition. Furthermore, continuous monitoring enables earlier detection, which allows the extension of the component's remaining useful life through modified operation.

> SI's recent advances with thick-film are breakthrough technologies for long-term monitoring and imaging of crack growth in critical components.

Given the trend of fewer on-site resources and tighter O&M budgets, the energy industry has a strong motivation to progress toward condition-based inspection and maintenance. To facilitate this evolution in asset management strategy, new monitoring sensor technologies are needed, ones that provide meaningful monitoring data directly correlated to the condition of the material or asset. To support this need Structural Integrity has developed a novel thick-film ultrasonic sensor solution. Initially developed for basic applications, such as thickness monitoring, SI's recent advances with this technology make long-term monitoring and imaging of crack growth in critical components possible.

BACKGROUND

Ultrasonic thick-films are comprised of a piezoelectric ceramic coating that is deposited on the surface of the component that will be monitored. A conductive layer is then placed over the ceramic layer, and the ceramic layer deforms when an electric potential is applied across the film. When a sinusoidal excitation pulse in the ultrasonic frequency range is applied across the film, the vibration of the film is transferred into the test component as an ultrasonic stress wave.

Structural Integrity initially developed our thick-film ultrasonic sensors for real-time thickness monitoring and has demonstrated the performance and longevity of this technology through laboratory testing and installation in industrial power plant environments,

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FIGURE 1. Installed thick-film UT sensors for thickness monitoring of elbows.

as seen in the photograph in Figure 1, where the sensors have been installed on multiple high-temperature piping components that are susceptible to wall thinning from erosion. In this application, the sensors are fabricated directly on the pipe's external surface, covered with a protective coating, and then covered with the original piping insulation. Following installation, data can either be collected and transferred automatically using an installed data acquisition instrument, or a connection panel can be installed that permits users to acquire data periodically using a traditional off-the-shelf ultrasonic instrument. Example ultrasonic datasets are shown in Figure 2.

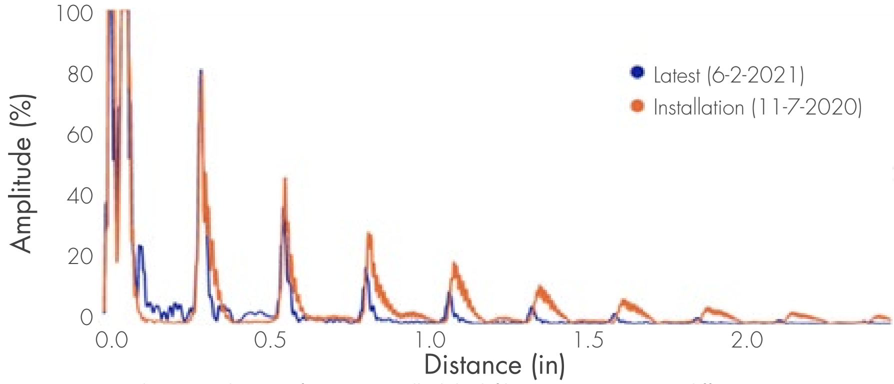

FIGURE 2. Ultrasonic datasets from an installed thick-film UT sensor at two different points in time.

TECHNOLOGY ADVANCEMENTS

Recently, SI has demonstrated the ability to create thick-film sensors with complex element arrays that can be individually controlled to steer and focus the sound field, as with traditional phased-array ultrasonic testing (PAUT). Moreover, data from individual array elements can be acquired and post-processed using full-matrix capture (FMC) techniques. FMC is a data acquisition technique where all elements in the array are used to both transmit and receive ultrasonic waves. The result is a large data matrix that can be used for further processing with various post-processing techniques. Compared to more traditional active focusing, FMC is well-suited for a fixed transducer array, as scanning speed is not a concern. Another advantage is that the electronics needed for data acquisition can be simplified – requiring only a single pulsing channel. A thick-film Linear-Phased Array (LPA) installed on a standard calibration block is shown in Figure 3. The two images shown on the right were generated using the Total Focusing Method (TFM) post-processing algorithm, with the image on the far right having an adjusted color scale to highlight the imaging of the notches toward the bottom of the calibration block. TFM is an amplitude-based image reconstruction algorithm where the A-scans from the FMC dataset are used to synthetically focus on every point in a defined region of interest.

Using other information from the FMC dataset, such as the phase of the waveforms, has proven to be beneficial in certain cases. At each focal point in the region of interest, a large phase

FIGURE 3. FMC TFM results from a thick-film linear phased array installed on a calibration block.

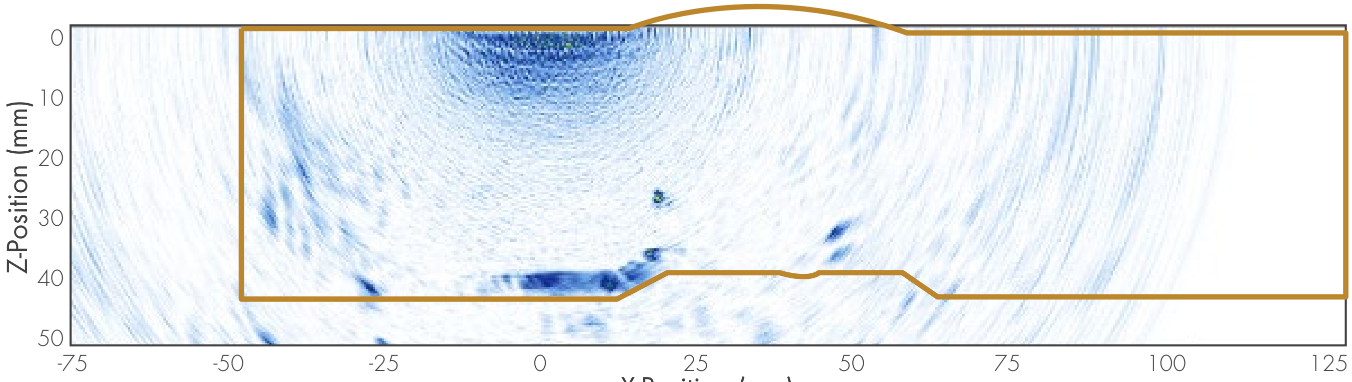

FIGURE 4. Phase coherence imaging result from a thick film transducer array on a cracked weld sample.

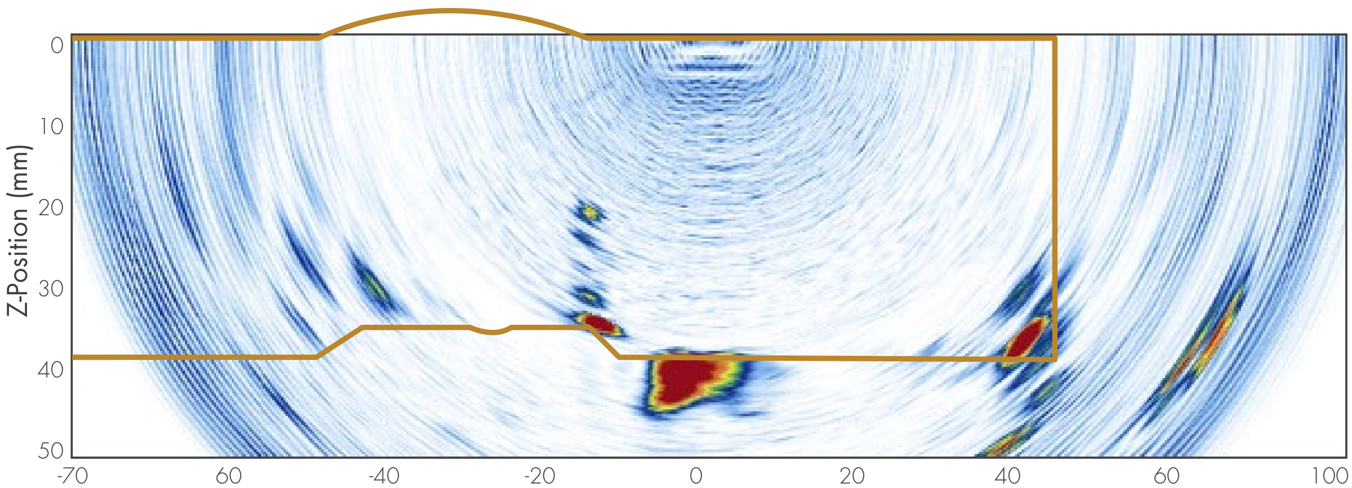

FIGURE 5. Phase coherence imaging result from a thick film transducer array on a cracked weld sample.

coherence among all the waveforms can be indicative of a focused reflector. This can then be applied to the TFM image at each focal point as a weighting factor (also known as the Phase Coherence Factor (PCF)) to improve the signal-to-noise ratio. Figures 4 and 5 illustrate the results of applying the phase coherence imaging technique to the FMC datasets collected with thick film transducer arrays. The sample is a section of high-energy piping approximately 1.7 inches thick with cracking at various positions along a girth weld. The sample has a counterbore with ID-initiated cracks up to approximately 0.5 inches in length coming from the taper of the counterbore. The thick film transducer arrays were located at different positions along the weld.

SUMMARY

The energy industry is moving away from traditional scheduled-based planning for inspection and maintenance activities and toward “smart plant” concepts that rely more heavily on data correlated to actual component conditions. To accomplish this, there is a need for new and novel monitoring technologies that are both unobtrusive and able to withstand the harsh conditions of industrial facilities. Collecting robust and meaningful monitoring data will be critical in ensuring that safety and asset reliability are maintained and even improved. Structural Integrity’s thick-film UT technology has been developed to achieve this goal and continues to evolve for higher-temperature components and more advanced applications. We are ready to support a variety of in-field applications, contact one of SI’s experts if you have questions or a potential application that could benefit from installed thick-film UT sensors.