2016

VOLUME
41

Structural Integrity Associates, Inc.®

NEWS & VIEWS

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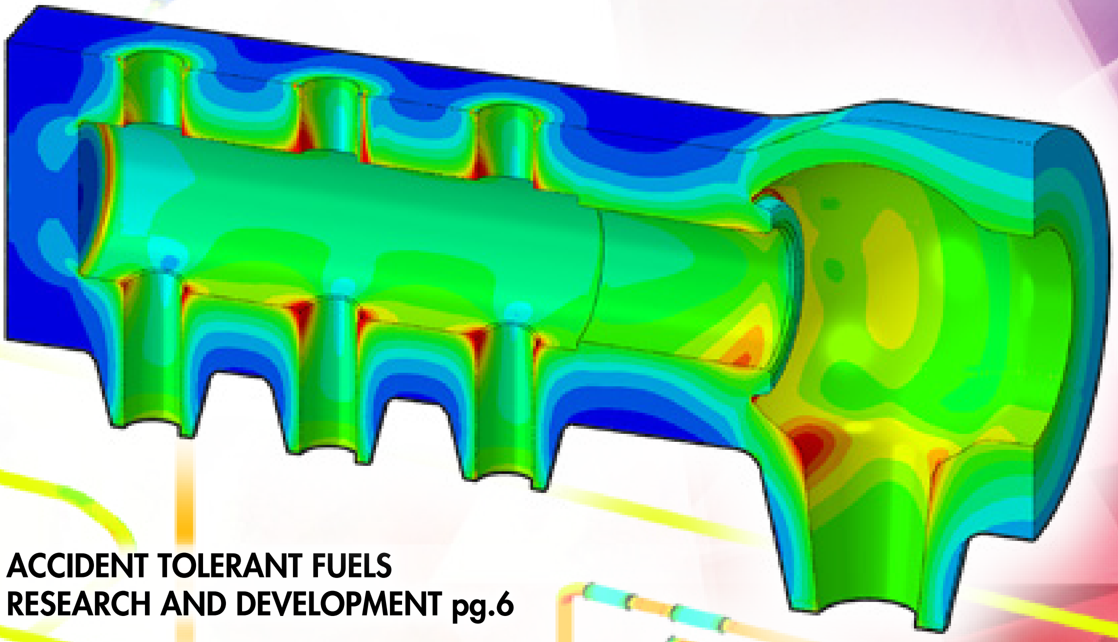

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PRESIDENT'S CORNER

Structural Integrity
Associates, Inc.®

By: LANEY BISBEE
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After 33 years in business, we've now gone and done it – we have entered the electrical consulting business. Just like our additions of chemical engineering and nuclear fuel, we continue to expand our core competencies beyond mechanical engineering, materials and NDE, this time through a few key hires.

At Structural Integrity Associates, Inc., we are known for applying our broad range of core competencies to critical plant components in accordance with our Mission Statement:

Be the most trusted, independent provider of innovative, best in value, fully-integrated asset lifecycle solutions.

The objectives of our Lifecycle Solutions have always been:

- Address potential failures with extraordinary consequences, even if low probability
- Address high probability failures, even though consequences may not be catastrophic
- Extract as much useful life from components as possible before implementing repair/replacement without assuming undue risk
- Provide reliable run/repair/replace options to optimize operational effectiveness and maximize planning options

Given our historical bias toward mechanical and materials engineering disciplines, we typically applied our lifecycle solutions to tubes, pipes, valves, turbines, pressure vessels and other pressure retaining components. While failure of these components are a low probability (except for boiler tubes), they can be of extraordinary consequence. For those of you that know, just think of a turbine disk burst, a longitudinal seam weld failure, a CRDM weld failure or a buried hazardous liquid or gas pipeline failure. They all present significant personal safety and property damage risk.

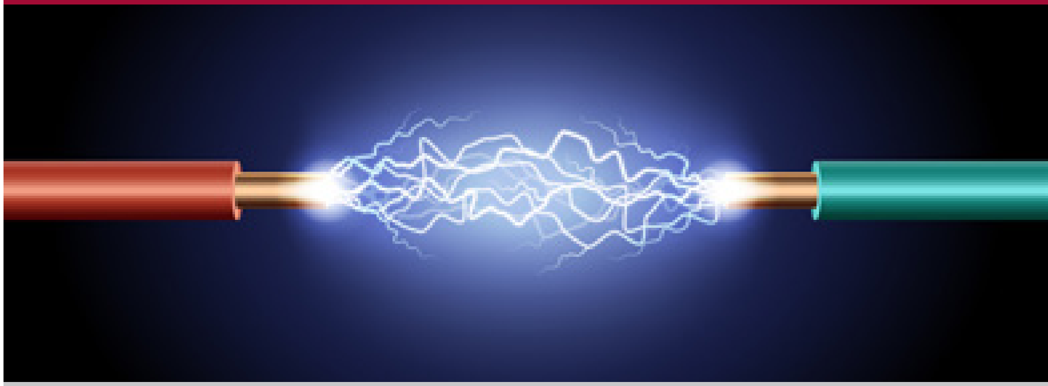
While preventing failures and extending component life is critical to the plants we support, data shows that a significant majority of nuclear plant shutdowns occur because of electrical equipment failures, not pressure retaining components. So electrical component failures are a higher probability event, albeit with reduced consequences to personal safety and property damage, but they do significantly impact plant reliability and availability. Therefore, in keeping with our mission statement, we are expanding and diversifying our technical expertise to offer electrical component asset lifecycle solutions. Specifically, we provide electrical equipment aging management support and equipment environmental qualification (EQ) services. We will also provide consulting in equipment design or adaptation to nuclear and harsh environments as well as engineering consulting for harsh/unique environment testing. While our new employees have direct experience in the nuclear market, we anticipate their services will also prove useful across all industries we serve.

You may recall that I previously discussed our increased focus on innovation with the formalization of our strategic development process. Outcomes of this process may be

new tools, inspection techniques, software applications or products for manufacture and sale. I mention this because a core competence of our electrical consultants is the development of niche products. It is expected that their consulting work will drive the identification of critical industry needs that can be met through the development of nuclear and harsh environment qualified products. Through such products, we can broaden our client reach and solution set.

Overall, we are thrilled to offer our clients both specific electrical solutions as well as more broadly integrated lifecycle solutions.

STRUCTURAL INTEGRITY LAUNCHES NEW ELECTRICAL SERVICES



PRINCIPALS OF ENGINEERED SOLUTIONS GROUP JOIN STRUCTURAL INTEGRITY TO LEAD NEW VENTURE

To better serve our clients, Structural Integrity routinely taps the talent of industry-leading people and partners whose expertise complements our own. Working together, we are able to provide some of the industry's most advanced turnkey solutions. And our menu of offerings continues to grow.

In this spirit of growth, Structural Integrity is pleased to announce it has expanded its engineering services to include an electrical consulting group. Leading the new group are Rick Easterling, Bob Minadeo and Ed Hurley, former principals of Engineered Solutions Group LLC, who joined Structural Integrity as full-time employees in June.

Drawing on their vast experience, this talented trio will develop a scalable electrical consulting offering specializing in electrical systems analysis, electrical aging management support and equipment qualification (EQ) services. They will also consult on equipment design or adaptation to meet the requirements of nuclear and harsh environments.

The Structural Integrity team includes some of the brightest minds in the business. The addition of Easterling, Hurley and Minadeo only deepens our pool of talent.

The three entrepreneurs have decades of experience with many utilities in the U.S. and Canadian nuclear fleet, as well as many of the equipment manufacturers, architect engineering firms, test labs, and consulting firms that serve them. They leveraged this broad industry experience and passion for problem-solving to form Engineered Solutions Group in 2012.

As long-time leaders in the industry, Easterling, Hurley and Minadeo developed deep roots and respect in the nuclear power industry. We expect their electrical consulting services will soon be sought after across all industries we serve.

Our newest team members are ready to hit the ground running! To put their experience to work for you, call 1-877-4SI-POWER or email us at info@structint.com.

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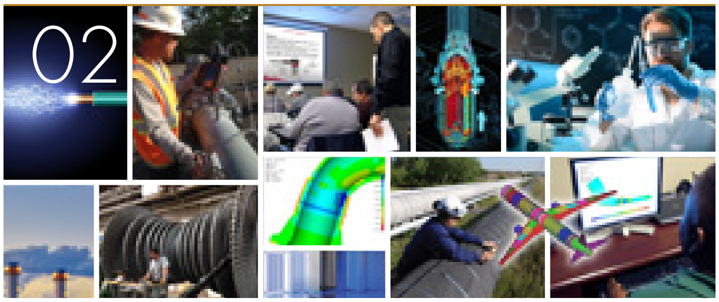

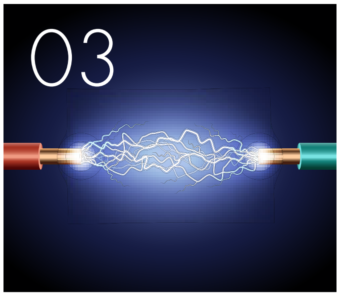

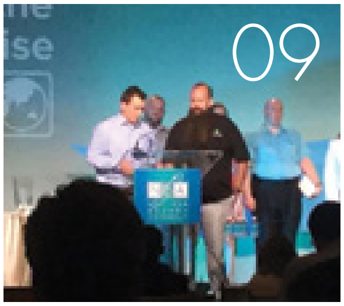

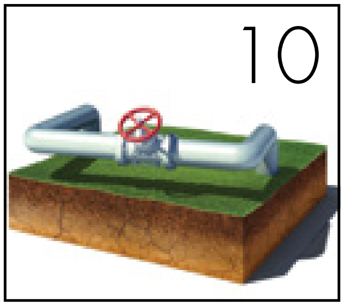

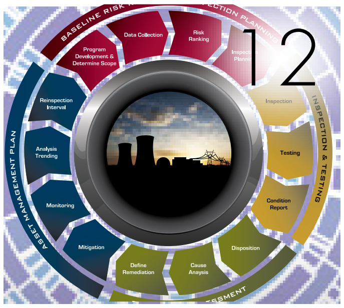

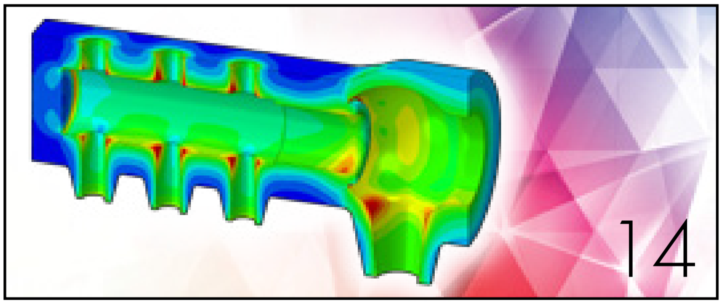

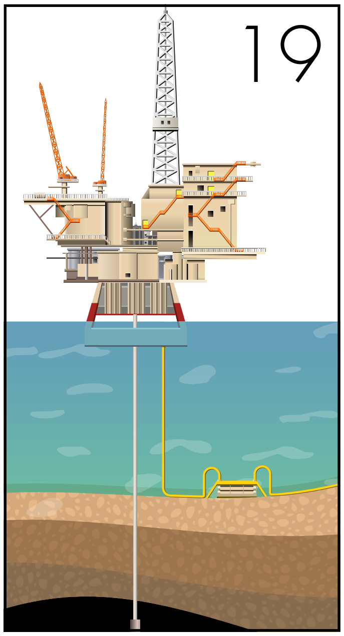
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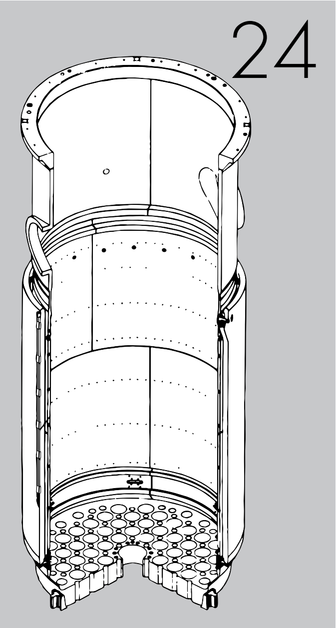
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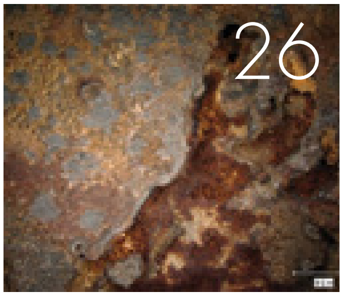
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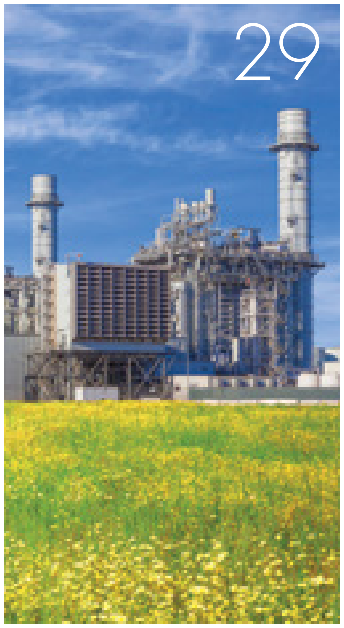
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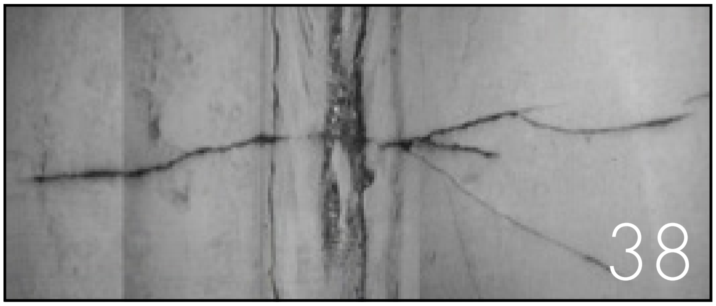
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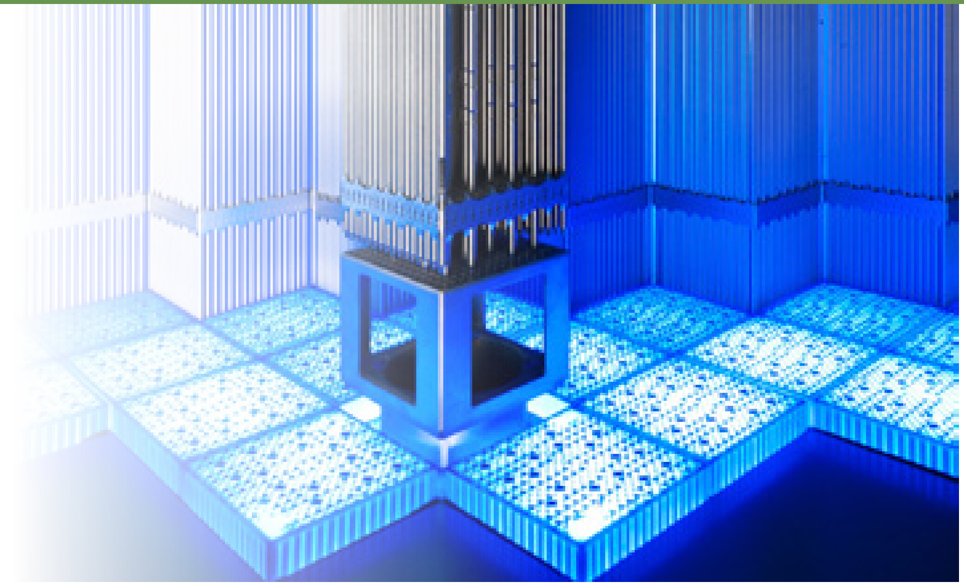
ACCIDENT TOLERANT FUELS RESEARCH AND DEVELOPMENT



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Intense interest in improving the response and survivability of nuclear power systems began as a consequence of the accident at the Fukushima Daiichi nuclear power plant in 2011. The damage from the massive tsunami lead to a station blackout which eventually caused loss of cooling and the generation of steam and hydrogen (from the Zirconium-steam reaction) in the reactors that resulted in hydrogen explosions and radioactive contamination to the environment. This event lead to a serious discussion in the United States about improving the accident tolerance capabilities of light water reactors (LWRs) and prompted the Department of Energy (DOE) to initiate a program focused on developing new fuel forms, with an emphasis on improving the fuel's response to accident conditions while still maintaining or improving current steady state operation.

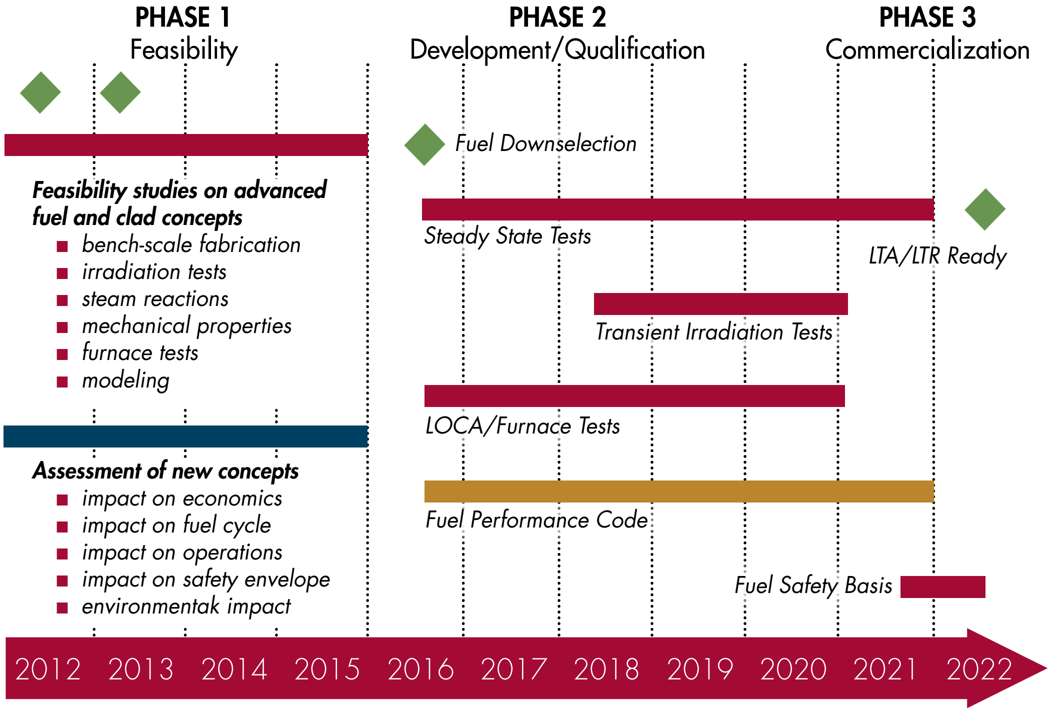

Figure 1. U.S. DOE ATF Program timeline and plan for Research and Development

THE PRIMARY ISSUES

The U.S. nuclear fleet utilizes uranium dioxide (UO2) fuel pellets clad in Zirconium-based alloys as its fuel form. This fuel design has inherent performance limitations under accident conditions. The development of accident tolerant fuels (ATFs) is specifically designed to address these limitations. To achieve this goal, ATFs must improve upon the specific material limitations present in conventional nuclear fuels that create vulnerabilities. The primary vulnerabilities include:

- Steam Reaction Kinetics: A rapid exothermic process in which Zirconium and steam react at high temperatures resulting in extensive cladding oxidation and production of hydrogen gas.

- Hydrogen Embrittlement: Zirconium hydride formation as the result of hydrogen ingress which creates localized cladding embrittlement.
- Thermo-Mechanical Response:
  - Cladding – During a LOCA there are multiple issues that need to be considered including thermal-shock resistance during emergency coolant injection, ballooning, oxidation, hydrogen ingress, and melting that can lead to cladding failure.
  - Fuel – Current limitations in UO2 fuel forms include relatively low thermal conductivity and potential for melting, fragmentation, relocation, as well as reduced fission product retention and the related potential for fission product dispersal into the reacter coolant system after cladding failure. Additionally, fuel-cladding chemical and mechanical interactions, as well as the stored heat during normal operations prior to the initiation of an accident can exacerbate the effects of reactor accidents.

ATF TIMELINE

The advanced fuels campaign has embarked upon an aggressive schedule for the development of enhanced accident tolerant LWR fuel system concepts (See Figure 1). The program has recently entered the second phase of research and development and is currently supporting the investigation of a number of candidate technologies lead by commercial fuel vendors: Westinghouse, AREVA, and GE (see Figure 2). The overall ATF development goal is to demonstrate the fuel technology's performance by inserting a lead fuel rod or lead fuel assembly into a commercial power reactor by 2022, with deployment in the U.S. LWR fleet to follow within 20 years. The ATF technology deployment timeline for insertion of a lead fuel rod into a commercial reactor is:

- **Phase 1: Feasibility Assessment and Down-Selection** – Development of fuel concept, testing and evaluation of material properties, steam reactions, and irradiation test (FY2012-FY2016).
- **Phase 2: Development and Qualification** – Fabrication of prototypic fuel rodlets and irradiation experiments in test reactors under LWR operational conditions (FY2016-FY2022).
- **Phase 3: Commercialization** – Insertion of an ATF fuel rod or assembly into a commercial nuclear reactor, partial core reloads, testing to verify ATF performance capabilities, and support nuclear regulatory licensing (+FY2022)

AREVA

- Develop coated Zr-alloy cladding for improved accident performance
- Increased fuel pellet conductivity: Fuel with reduced stored energy that must survive DBE- a design basis earthquake
- Additives achieved:
  - SiC powder or whiskers
  - Diamond
  - Chromia dopant

GE

- Develop advanced ferritic/martensitic steel alloys (e.g., Fe-Cr-Al) for fuel cladding to improve behavior under severe accident scenarios
- Objectives:
  - Characterize candidate steels
  - Study tube fabrication methods, neutronics, fuel economy, thermo-hydraulic performance, regulatory approval path
  - Initiate ATR testing with UO2 and cladding materials.

WESTINGHOUSE

- Develop and test cladding concepts: SiC and SiC ceramic matrix composites; coated Zr alloys
- High density/high thermal conductivity fuel pellets (e.g., uranium nitride/silicides)
  - First batch of U3Si2 pellets were sintered using finely ground powder
  - Pellets were pressed using pressures of 6,000-10,000 psi and sintered at temperatures of 1400°C

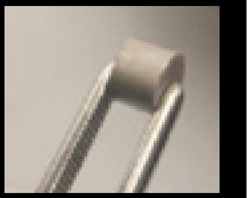

Figure 2. Three industry lead teams and ATF concepts

ACCIDENT TOLERANT FUELS RESEARCH AND DEVELOPMENT

CONTINUED

INDUSTRY TEAMS AND ATF CONCEPTS

The ATF program is at the end of Phase 1, and has been supporting the investigation of several technologies that look to improve fuel behavioral response during steady state operations and during accident conditions. DOE has been sponsoring three industry lead teams led by Westinghouse, AREVA, and GE to develop ATF technologies. Besides the fuel vendors, each team comprised of national laboratories, universities, and other nuclear organizations within the industry. The concepts being investigated by these teams include:

- Cladding coatings, such as Ti2AlC, on to the cladding outer surface to provide resistance to oxidation, hydrogen pick up, and corrosion. (see Figure 3)
- Substitute cladding materials such as advanced stainless steels, iron-chromium-aluminum (FeCrAl), and ferritic stainless steels, to decrease void swelling and enhance resistance to irradiation assisted stress corrosion-cracking.
- Fuel pellet dopants and alternative materials such as chromia for fission product retention, silicon carbide whiskers or nano-diamond particles to increase the fuel thermal conductivity, and uranium silicide (U3Si2) to improve thermal conductivity and increase uranium content.
- Longer term concepts such as silicon carbide (SiC) cladding material (see Figure 3), SiC is resistant to oxidation and corrosion which reduces hydrogen production and hydrogen uptake, has very high strength eliminating cladding ballooning, and utilizes a uranium nitride fuel matrix which offers high thermal conductivity and heat capacity.

At the start of Phase 2, each research team will begin irradiation of ATF concepts in the Idaho National Laboratory Advanced Test Reactor.

ATF ACTIVITIES

Structural Integrity's Fuel Group contributed to the development and evaluation of several ATF concepts through participation in EPRI and DOE-sponsored research and development programs as is described in the following paragraphs.

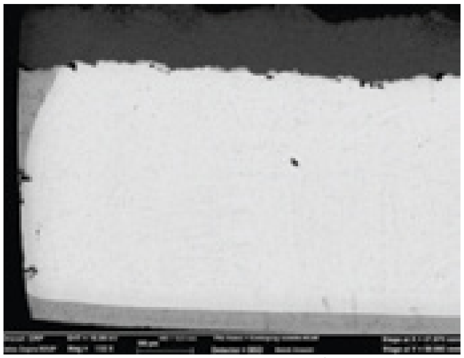

Figure 3. Cross section of a Ti2AlC coated Zircaloy coupon after steam oxidation under LOCA conditions

SiC CLADDING EVALUATION

This project, sponsored by EPRI through the Long-Term Operations (LTO) Program, was comprised of several tasks focused on fuel rod performance calculations to evaluate the potential for SiC cladding to achieve burnup levels, approaching 100 GWd/tU. Initially, a review of work performed by MIT using a modified version of the FRAPCON code was completed [Ref 2]. We then adapted a set of MIT-derived SiC material thermal and mechanical properties and implemented them in the Falcon code. Comparative studies were then completed using Falcon to evaluate the performance of several proposed SiC-clad fuel designs comparing to a conventional Zr-based fuel rod under simulated long term PWR irradiation conditions. An additional task completed during this work was the simulation of and comparison to mandrel mechanical testing of SiC tubing samples conducted at ORNL (See Figure 4 and 5) [Ref 3]. A final project report was completed and published by EPRI [Ref 4].

Figure 4. Proposed prototype SiC composite cladding tube sample

TZM-BASED COMPOSITE ALLOY CLADDING

We completed a series of preliminary evaluations of a proposed Titanium Molybdenum Zirconium (TZM)-based composite alloy cladding material using the Falcon fuel performance code. As with other proposed alternative cladding materials, the goal of this proposed composite design was to utilize a high strength alloy to limit cladding ballooning and deformation, coupled with several prototype coatings to limit cladding oxidation, hydrogen production and embrittlement.

DOE-SPONSORED BISON ATF APPLICATIONS

We participated as a code developer supporting the DOE Nuclear Energy Advanced Modeling and Simulation (NEAMS) Initiative and the BISON fuel performance code. Beginning in 2015, an ATF component has been added to our support work scope. The ATF evaluation involves two areas of development for the MOOSE-BISON system: (1) the development of material models for new cladding and fuel materials, and (2) the development of capabilities for LOCA transient flow regimes.

The first area involves the preparation of material behavioral models for silicide fuel-pellet material and cladding

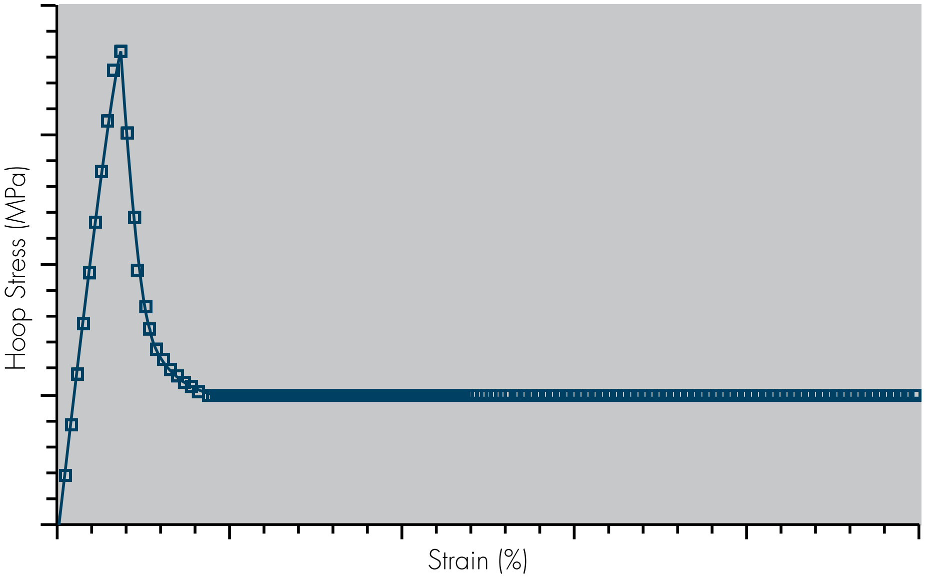

Figure 5. Falcon mandrel test simulation illustrating cracking material response for simulated SiC tubing

alloys such as Iron-Chromium-Aluminum (FeCrAl, see Figure 6), or a composite cladding made of TZM alloy between two zirconium-based alloy layers. This capability will be implemented first, building on our prior work in this area for EPRI. The second area requires the modification of the coolant channel model to treat flow restrictions due to cladding ballooning. This requires the addition of a flow model to the existing enthalpy-rise closed channel model currently in BISON. Our current effort has been focused on developing empirical models to account for flow restriction effects and applying coolant channel heat transfer correlations.

Figure 6. FeCrAl tube developed at ORNL

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IN THE NEWS

JAEGER AND SPEAR WIN INNOVATION COMPETITION

Earlier this year, Structural Integrity's Mark Jaeger and Duke Energy's Jeff Spear returned from the Annual Nuclear Energy Assembly and NAYGN Professional Development Conference with more than business cards and fresh ideas.

In fact, their own fresh idea took top honors in the 2016 Innovation Competition sponsored by the North American Young Generation in Nuclear (NAYGN). The duo won the award for their concept for street view nuclear plant tours.

The conference, held May 23-25 in Miami, drew hundreds of industry leaders and policymakers from around the world. As winners of the competition, Jaeger and Spear will be given the opportunity to meet with top nuclear executives to discuss the possibility of implementing the idea across the industry.

Congratulations to Mark and Jeff for their big win and spirit of innovation!

Considerations When Establishing a 192.607 Material Verification Program

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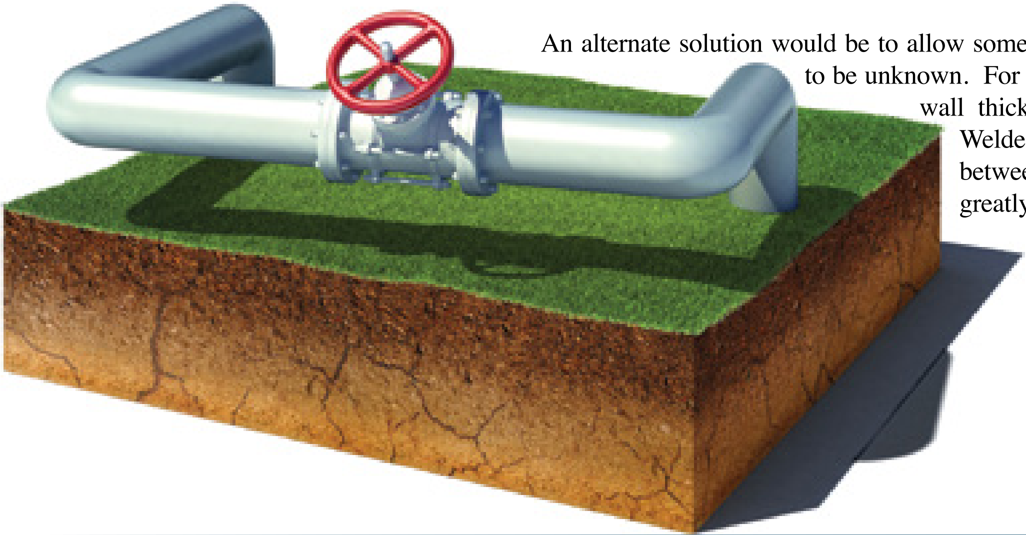
In the April 8, 2016 Federal Register, The Pipeline and Hazardous Materials Safety Administration (PHMSA) issued a notice of proposed rulemaking (NPRM) entitled "Safety of Gas Transmission and Gathering Pipelines." The proposed regulation will pose very significant challenges to the gas transmission industry. As you may have heard in our webinar at the time, one of the most significant is the proposed addition of 49 CFR §192.607, the material testing requirement. In brief, this section will require material testing (destructive or non-destructive) to determine material properties of pipeline segments, valves, flanges and components with inadequate material property records. Although the section is quite prescriptive, many questions remain regarding its implementation. The answers to these questions will have a profound effect on the value, and cost, of an operator's material verification program.

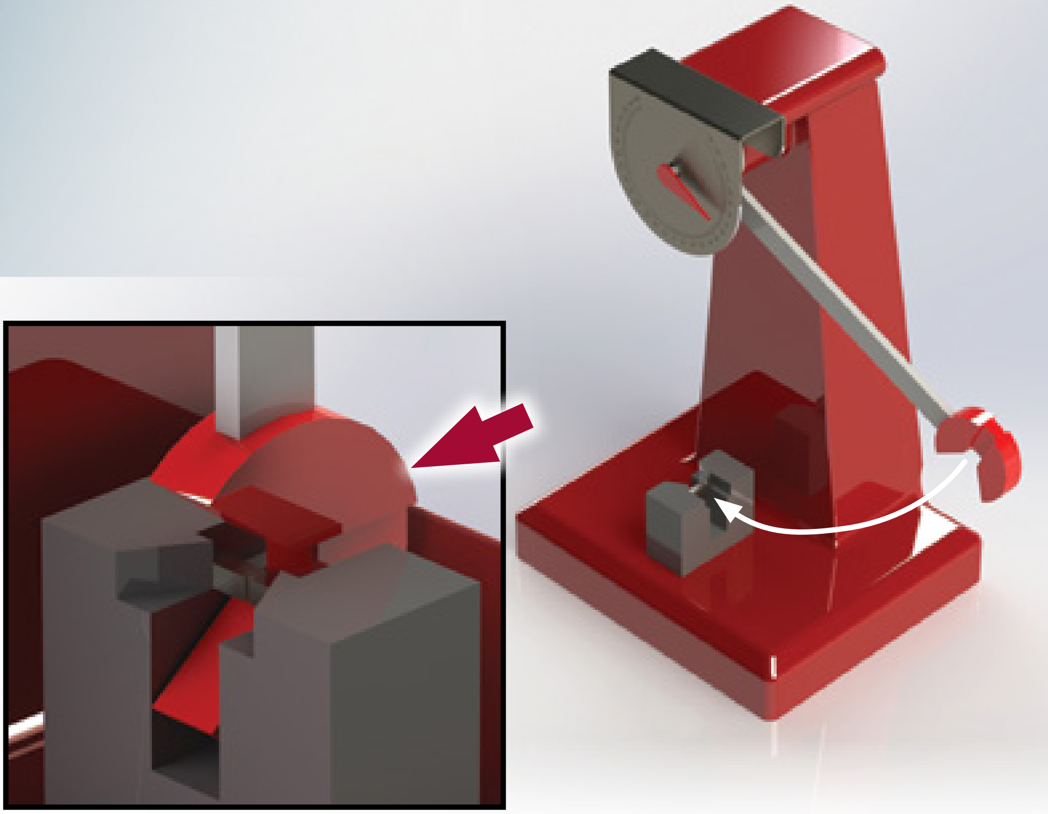
WHAT IS A "POPULATION" AND HOW ARE "POPULATIONS" TO BE DEFINED?

The proposed rule requires that an operator define populations of pipe to be tested, for purposes of defining the number of tests required. Specifically, a separate population is required for unique combinations of the following characteristics: wall thickness, grade, manufacturing process, pipe manufacturing date (within two-year interval), and construction date (within two-year interval). Unfortunately, it is difficult to identify populations when there are no records to indicate the characteristics required to sort. In fact, lack of complete records is the reason the segment is being sorted in the first place.

Two solutions are apparent. One possible solution would be to review all available documentation, not just that considered Reliable, Traceable, Verifiable, and Complete (RTVC), and assign attributes to each segment no matter how weak the evidence. The operator may wish to consider the contents of the GIS system, documents failing to meet RTVC criteria, construction standards, purchasing standards, and subject matter expert testimony. Prioritization criteria could be established to collect data from the most reliable sources first. Once a thickness, grade, etc. is assigned to each and every pipeline segment, populations can be defined. The challenge with this approach is, first, data collection is likely to be costly. Secondly, the use of less reliable sources increases the likelihood of inconsistent test results, thus increasing the number of required tests.

An alternate solution would be to allow some of the sorting characteristics for a segment to be unknown. For example, one population may be 0.250 inch wall thickness, grade unknown, Electric Resistance Welded (ERW), manufactured and installed between 1974 and 1976. Such an approach would greatly simplify data collection because operators can simply query their database of RTVC record data to define populations. However, the example population would likely contain pipe segments of more than one grade. How are populations to be re-organized when material testing data indicate different grades within the same population? The challenge is that linear pipe segments are to be sorted based on data collected only at points.





Charpy V-Notch Impact Testing

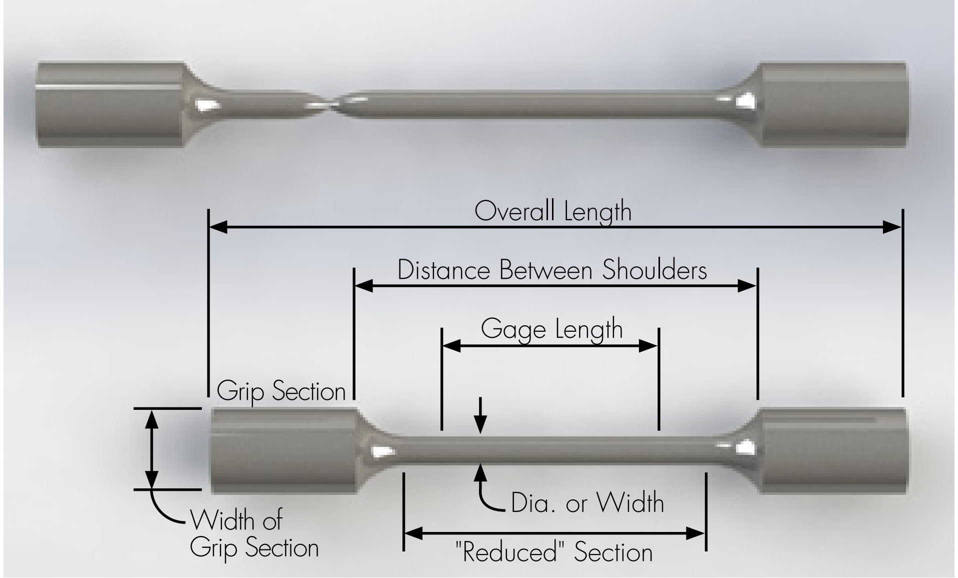
WHAT DOES IT MEAN TO HAVE AN 'INCONSISTENT' TEST FINDING?

The proposed 192.607(d)(3)(viii) requires that "if the test results identify line pipe with properties that are not consistent with existing expectations based on all available information for each population, then the operator must perform tests at additional excavations." Exactly what constitutes "all available information" is a very important question. If it extends beyond data that can be queried from a database, collecting such information and comparing to material test results could be quite challenging.

In addition, how far off does a finding need to be in order to be inconsistent? Whatever test method is chosen, there will be some measurement uncertainty. This needs to be taken into account, in combination with the fact that API-5L specifies a range of acceptable values for properties such as wall thickness.

WHAT HAPPENS WHEN THERE IS AN 'INCONSISTENT' FINDING?

Suppose an operator has RTVC records for a pipeline segment indicating the grade is Grade B, and receives material testing results at a point on the segment indicating the yield strength does not meet the API-5L specification for Grade B. Perhaps the yield strength is only 30 ksi. Should the entire segment now be considered Grade A? The entire population? All pipe from the same mill or same construction project? What if other tests on the segment do meet the Grade B specification? More importantly, if a segment does have a lower grade assigned, is it now considered "grandfathered", thus requiring inclusion in the operator's Integrity Verification Program?



Tensile Specimen (Stress vs. Strain)

A carefully considered Material Verification Plan will address these and other issues. Structural Integrity recommends that operators initiate their material verification program immediately. The information that can be gained from testing on an opportunity basis is very valuable, and may aid in decision making. In addition, the experience gained in the early years will help to ensure that the material verification program runs smoothly once the rule is finalized.

At Structural Integrity, we advocate a data-driven approach to Integrity Management backed by seasoned professionals. Our solutions have enabled clients to implement traceability and data integration in a manner that is efficient, robust, and intuitive. Thinking through all the issues presented by the proposed rule requires a significant investment of time and effort. Such an investment will pay off as the program unfolds, resulting in more effective use of capital and operating budgets and a safer gas pipeline infrastructure.

MAPPro™ Cable for Effective Monitoring

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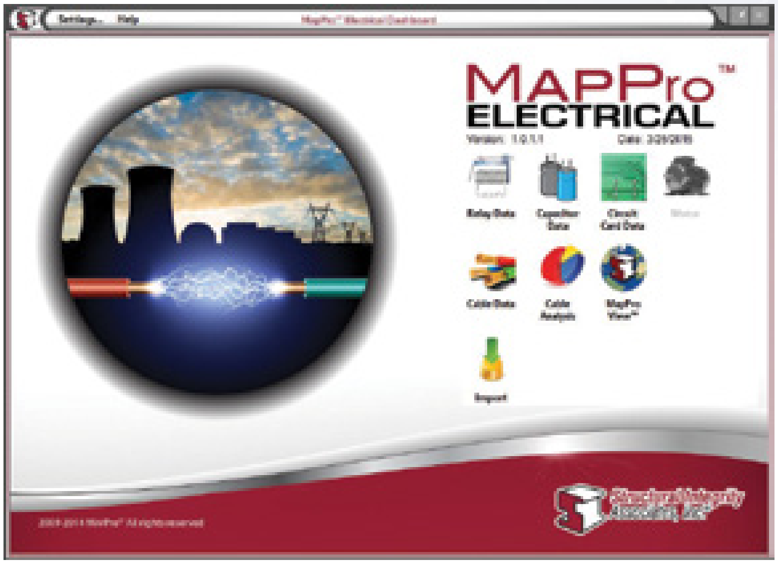
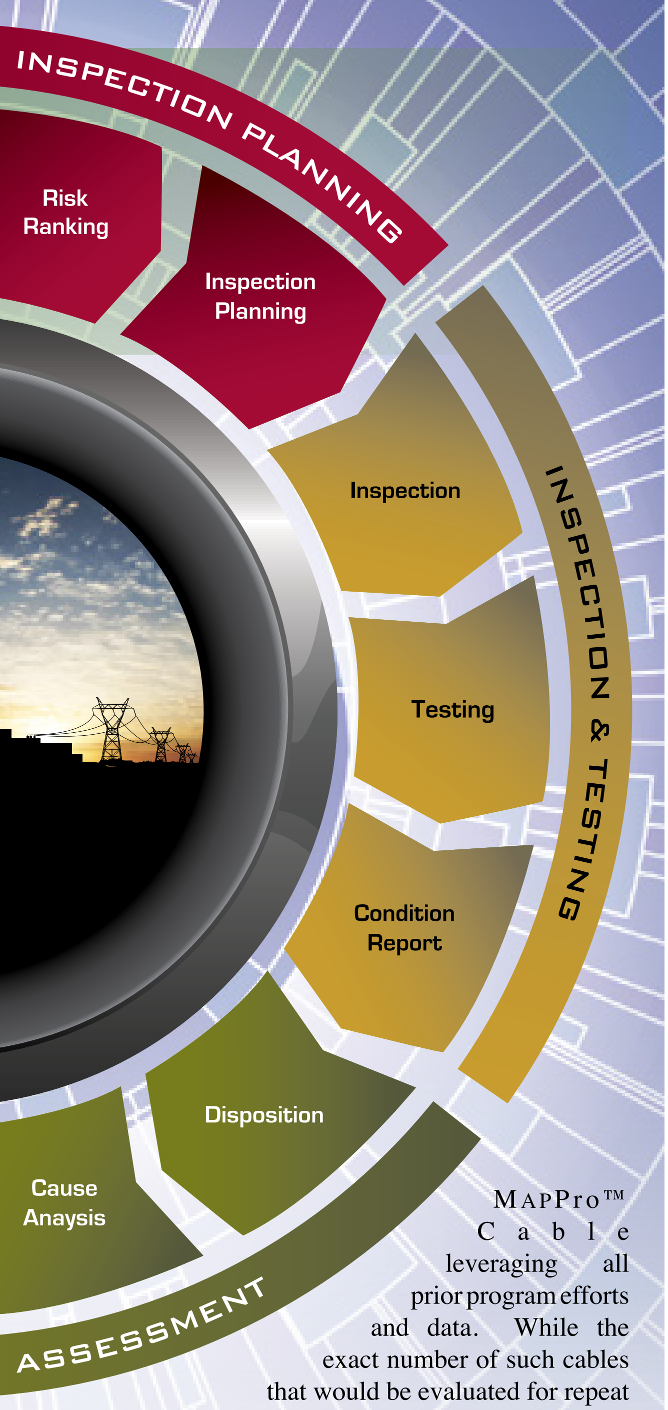
With today's economic pressures facing the nuclear industry, especially in the US where hydraulic fracturing has substantially lowered natural gas generation costs inputs and favorable regulatory treatment of renewable sources has supported solar and wind generation growth, managing plant program costs has become increasingly important. Cable aging management is one program where a thoughtful approach integrating risk insights and assessment of more severe environmental conditions can help limit the population of cables that need to be monitored. This is especially beneficial for monitoring low voltage cables.

Similar to the principles adopted for other types of inspections, such as steam generator tubing and buried piping, sample based inspections focused on more susceptible populations can be developed. Such an approach can provide a reduced population of leading indicator cable locations that serve as bell weathers for other plant cables. This approach is particular useful for low voltage cables where, again similar to steam generator tubes, large quantities of each are present in a plant.

Structural Integrity has adapted its successful buried pipe tool, MAPPro™, to include a software module to address cable aging management issues: MAPPro Cable. This innovative module is consistent with the widely deployed industry standard EPRI BPWorks 2.0™ data structure and is capable of supporting a complete cable aging management program. The module leverages a comprehensive set of information that's important to the effective management of cable aging mechanisms – ranging from design to aging environment to feedback from inspection results. Through use of these features, a risk ranked approach can be used to identify both the most risk important cables and the most degradation susceptible cables so that testing and monitoring efforts can be focused on a small set of cables, with scope expansion planned in a systematic way should degradation greater than anticipated be identified.



Existing cable program information gleaned from earlier walkdowns and plant data tracking tools can be loaded into



MAPPro™ Cable leveraging all prior program efforts and data. While the exact number of such cables that would be evaluated for repeat monitoring in this first category would vary by plant, it is expected that such a sample would comprise a few hundred cables that would be evaluated on a periodic basis over several years. This type of approach can help reduce the cost of activities related to cable aging management and monitoring program commitments. Furthermore, the module can be customized to perform more common cable calculations as well, such as cable loading, ampacity, and cable fill factor calculations to support broader use of the module for other plant configuration and design purposes. Other electrical modules for components such as motors, capacitors, and circuit boards and relays are also available or under construction with similar capabilities.

2016 NACE INTERNATIONAL LEADERSHIP PROGRAM

NACE International, the premier organization focused on the corrosion control of assets worldwide, conducted its inaugural International Leadership Program on June 21, 2016 – June 24, 2016 in Houston, Texas. From the broad list of applicants, only 24 were selected – representing corrosion professionals from five regions across the globe: North America, South America, Africa, Eurasia and Asia Pacific. Among those was our own Sr. Associate, Steve Biagiotti.

NACE's core purpose is disseminating knowledge, enhancing skills and expanding the professional networks for corrosion and asset protection professionals worldwide, through development and global delivery of state-of-the-art, outcome-based training programs.

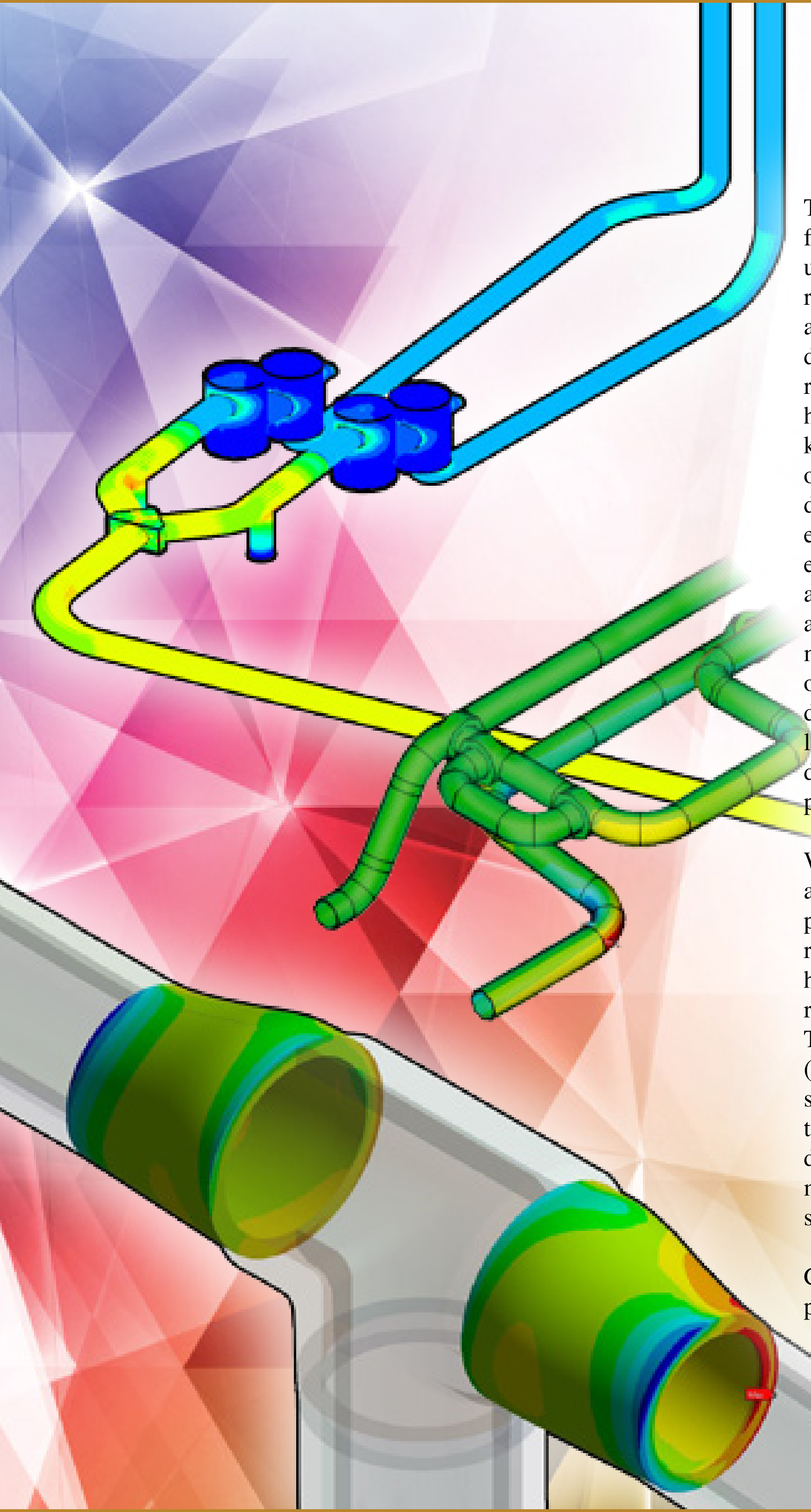
The NACE Leadership Program prepares members to ascend as leaders not only in their job and industry, but also within the NACE organization. Developed with NACE leaders in mind, students in the course participated in exciting discussion on topics including:

- Strategic Thinking
- Strategic Planning
- Awareness of Current & Future Industry Trends
- Association Management & Governance
- Coaching and Developing Others
- Interpersonal Relationship Skills
- And more…

Structural Integrity is a strong supporter of NACE International and other industry associations as we continue on our mission to deliver world class engineering solutions and strive to be the most trusted, independent provider of innovative, best-in-value, fully-integrated asset lifecycle solutions.

THE ROLE OF ADVANCED ANALYSIS IN EQUIPMENT LIFE CYCLE MANAGEMENT

By: ROBERT BROWN, P.E.
■ rbrown@structint.com



The safe and reliable operation of pressurized equipment in fossil power and process plants is a key objective of owner-users. Effectively managing the life cycle of this equipment requires an understanding of the numerous applicable standards and guidelines and integration of activities related to equipment design, in-service inspection and fitness-for-service/run-repair-replace decision making. The term life cycle management (LCM) has been adopted in recent years to describe this approach. One key to this process is identifying and understanding the resistance or structural response of pressure equipment to applicable damage mechanisms during service. While the initial design effort should have focused on providing adequate life for the expected service, it is not always possible to design completely against damage mechanisms due to cost, fabrication, scheduling and/or material related limitations. In addition, assumptions must be made during the design process regarding the anticipated operation. As a result, the term life-cycle management carries a double meaning. It involves planning how to manage the future life-cycle of equipment and is most accurately accomplished during the life-cycle of the equipment when actual in-service parameters and relevant damage mechanism's can be assessed.

Within the LCM framework, advanced analysis and life assessment can play a significant role in inspection planning/prioritization, fitness-for-service (FFS) decisions and repair/replacement strategies. The term advanced analysis is used here to represent numerical modeling of equipment to examine response to conditions such as pressure, temperature and flow. The analyses are typically performed using finite element analysis (FEA) or computations fluid dynamics (CFD) to simulate structural or fluid flow response. In both of these approaches, two or three-dimensional computer models are typically developed to represent the component geometry. Additional material properties and constitutive models are incorporated to simulate the physics of the problem being investigated.

Continuing advancements in technology and computer processing speed has allowed for development of more sophisticated simulation models that can more accurately represent complex material and structural response and the evolution of damage such as creep and fatigue. These models allow analysts to gain significant insight about the response and resistance of components and the effects of numerous variables related to damage that can be leveraged to target inspection locations, assess useable life and perform sensitivity studies. Linking of these models to operating data can be used to examine the effects of operational fluctuations such as changes in heating ramp rates and cycling on the long-term health of equipment on a real time basis. The implementation of advanced analysis can translate to more reliable and safe use of these assets as well as substantial economic benefit gained by a more in-depth understanding of equipment behavior and resistance to in-service damage.

Much of the pressure equipment in fossil power plants was designed in accordance with applicable standards such as ASME Section I, Rules for Construction of Power Boilers or ASME B31.1 Power Piping. As these are design and construction standards, prescriptive rules and design margins are typically employed to establish an intended conservative design basis. These codes typically do not provide rules to assess equipment (except in the case of B31.1, which states that there "…shall be a piping program" without giving clear guidance of what said program entails) that degrades while in service or from original fabrication flaws that may be found during inspections. These standards do not require advanced analysis or more rigorous design assessments to evaluate the effects of cyclic fatigue and creep, which are common damage mechanisms in fossil power plants. A very limited number of pressurized components are specifically designed for cyclic service and typically do not have the appropriate calculations performed to establish an allowable design life.

Fitness-for-Service standard API-579-1/ASME FFS-1 (API 579) provides assessment methods for reliable assessment of structural integrity of in-service equipment containing flaws or damage, or that may be operating under a specific condition that might cause a failure. Multiple analysis level options (Levels 1 through 3) offer the user a range of assessments from simplified screening to more rigorous advanced analysis. The assessment levels provide a balance between conservatism, data required for the evaluation, skill level of the FFS practitioner and analysis complexity. The Level 3 assessment typically involves numerical methods such as FEA. These more sophisticated analyses can be used in a predictive fashion since many of the conservative assumptions are removed and more explicit modeling of local stresses, strains and metallurgical conditions are performed.

It is common to use FFS in a reactive manner, for example making an FFS assessment to address recent inspection findings that may or may not have been anticipated. However, many users are utilizing FFS in a proactive way to more efficiently formulate a targeted inspection strategy as part of an LCM program. For the fossil power industry, Structural Integrity has implemented a comprehensive strategy for high energy piping (HEP) involving system analysis, inspection prioritization and life management. Our approach continually evolves to incorporate technical advancements in advanced analysis and material modeling, as well as practical industry experience to improve the accuracy of predictions of creep and fatigue damage, remaining life assessment, and identification of limiting locations for inspection.

Another key aspect of LCM for Fossil power plants relates to the expected service conditions for aging equipment. Much of the pressure equipment designed and fabricated more than 20 years ago was for base-loaded service with minimal operational cycling. These units are now being load cycled repeatedly, in some cases on a weekly or even daily basis to meet market demands. The load cycling can result in repeated thermal stresses during start-ups and shutdowns that can lead to irreversible damage beginning as micro-level plasticity and manifesting as macro level cracking from fatigue. These cyclic effects can also interact with creep, resulting in creep-fatigue interaction that can even further limit component life.

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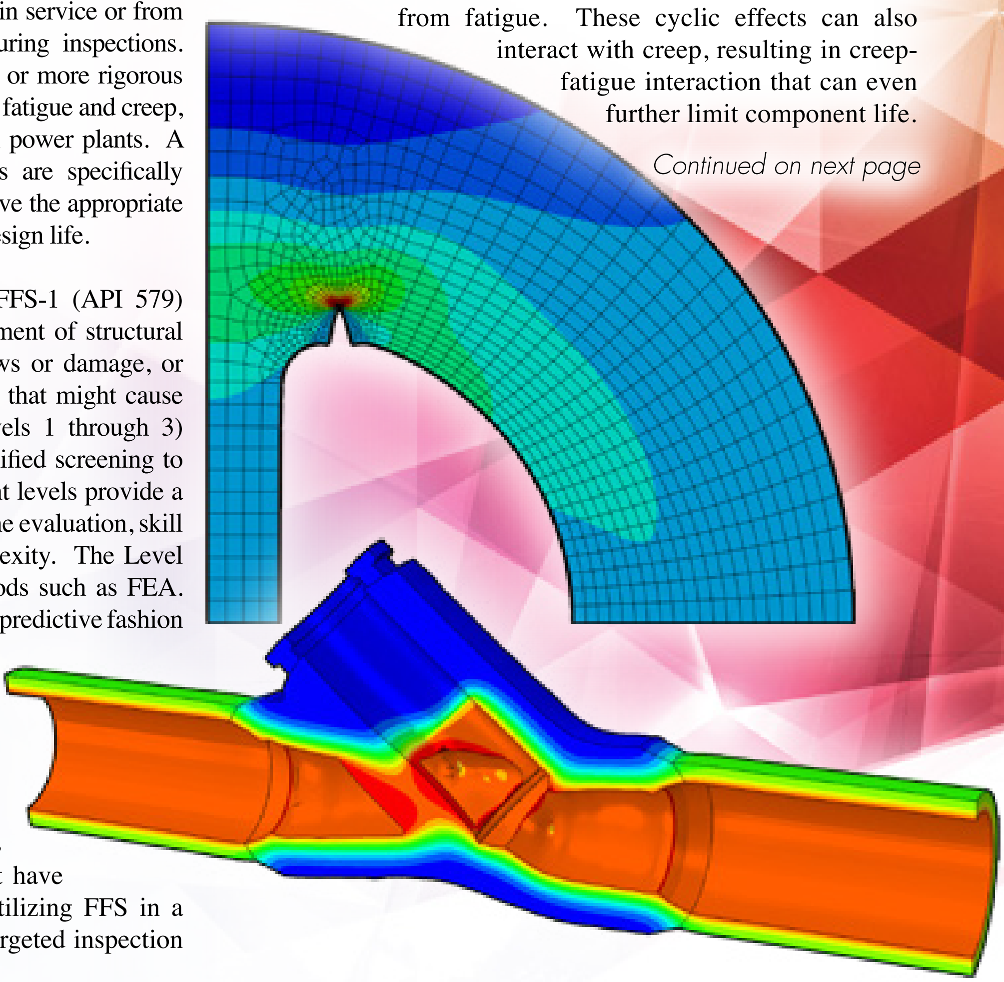


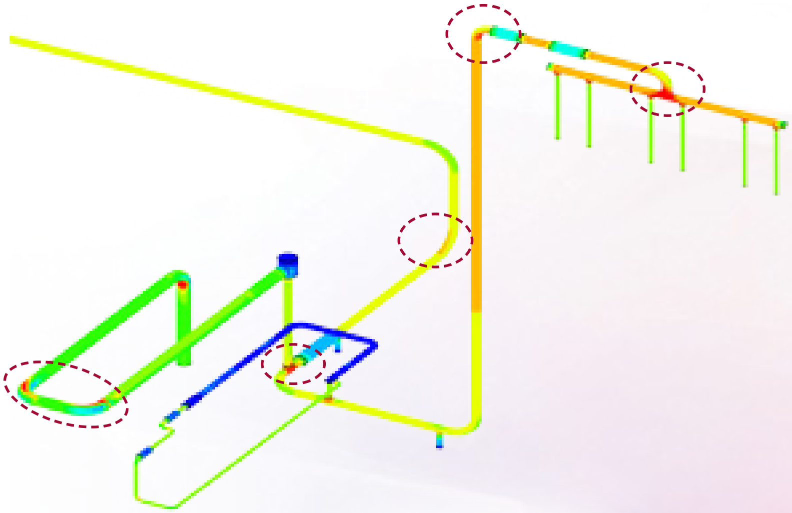
THE ROLE OF ADVANCED ANALYSIS IN EQUIPMENT LIFE CYCLE MANAGEMENT CONTINUED

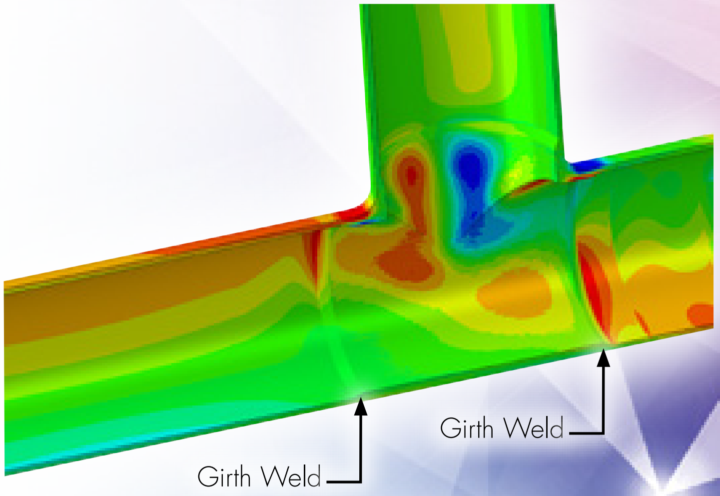
Two case histories are provided below to further illustrate applications of advanced analysis in fossil power plants.

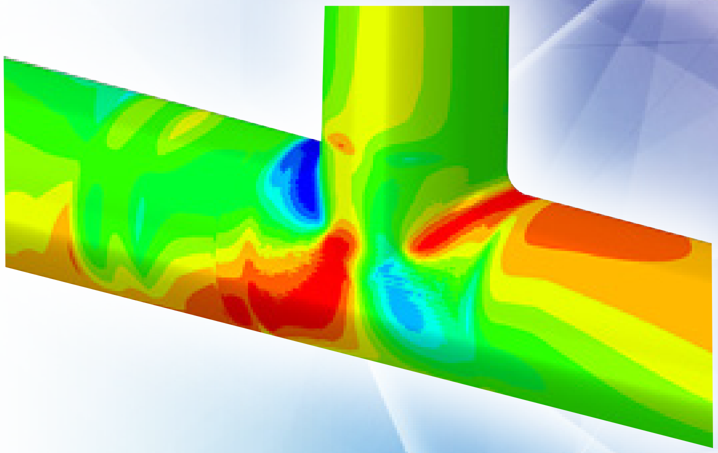
HRSG MAIN STEAM PIPING SYSTEM

A three-dimensional solid piping stress analysis was performed to examine the structural behavior of the main steam system, assess the remaining creep life and to prioritize in-service inspections. A key component of these assessments involves performing nonlinear FEA to simulate the relaxation of load and redistribution of stresses, as well as accumulation of strains resulting from high-temperature creep over time. Typically, design assessments are performed by others with simplified piping flexibility programs to establish basic compliance to ASME B31.1 or B31.3 allowable stress limits for sustained and thermal expansion loads. This approach relies on using specialized beam/pipe finite elements to represent the geometry and structural response of the system. This is effectively a centerline representation of a piping system that incorporates flexibility and stress intensification factors to approximate more complex three-dimensional behavior that occurs in piping components such as ovalization of elbows under bending loads or increased stresses at branch connections. These types of simplifications are instituted in an attempt to make the design process conservative. However, the factors were typically developed based on physical tests for a set of specific pipe and component sizes which have in cases been shown to be non-conservative. These factors were necessitated in the past to a strong degree by limited computer processing speed and solid modeling capabilities. Another key selling point to these simplified piping software programs was that it made the design approach and process tracible and consistent across organizations without necessarily requiring structural mechanics expertise.

An inherent limitation with this approach is the inability to capture the local increased stress distributions that occur at more complex geometric components and thickness transitions. These locations typically are associated with welds, which are generally more prone to creep and fatigue damage than base metal locations due to a number of factors related to metallurgy, residual stresses and the local increase in stresses at these material and geometric discontinuities. In addition to limitations with the geometric representation of the system, piping flexibility methods are based on elastic material behavior, so they can be particularly deficient for gaining real insight about piping operating in the creep regime as part of LCM.







Utilizing a detailed geometric representation of the system and material creep constitutive model allows for more realistic prediction of behavior that can be effectively used to assess creep life, prioritize inspection and perform what-if scenarios to evaluate support and hanger effects. The overall 3D solid model geometry and a typical plot of creep redistributed stresses in a portion of a HRSG main steam system are shown in the adjacent figures.

An additional benefit of utilizing 3D solid geometry is that local portions of the model can be refined based on actual field measured dimensions to more accurately assess stress distributions and damage accumulation rates for FFS assessments. Rather than creating separate local models and applied boundary constraints based on a separate full system analysis, local refinement permits more precise determination of stresses and stiffness effects as well as more precise assessment of how these refinements affect overall system behavior. An example of a more detailed local model is also provided of a 3D tee section. The figure plots axial stresses to highlight the improved fidelity of results using 3D solids including through-thickness and circumferential variation of stress (as well as accumulated creep strain and other damage variables) that would not be available with piping flexibility analysis.

A greater level of results resolution is important for performing creep lifing and assessing fitness-for-service, particularly for Grade 91 material. Relatively early damage detection in Grade 91 using advanced ultrasonics or other non-destructive techniques is much more challenging than for other low-chrome alloys; hence the need for more accurate simulations for predicting life as part of an integrated strategy.

PROACTIVE FFS ASSESSMENT OF STEAM CHEST

Finite element stress analysis was performed to assess the likelihood of service damage due to fatigue and creep in two identical geometry steam chests (see photo) that have been in operation for approximately 30 years. Our analysis work was used in a proactive way to identify key locations to inspect for cracking during the upcoming outage and to establish an expected life of the component. Performing this work ahead of the inspection allows for better understanding of component behavior, prediction of likelihood of damage and, most importantly developing least costly run-repair-replace strategies where needed rather than making a less-informed reactive decision upon discovering damage and unplanned repairs.

Detailed transient thermal, stress, and nonlinear creep analyses were performed to investigate the range of stresses during operation to assess the potential for fatigue and creep damage initiation. Since detailed design calculations of this nature are rarely performed, this work is important for predicting expected time to damage. Results of these analyses indicated that fatigue crack initiation may occur within 30 years of operation. Although,

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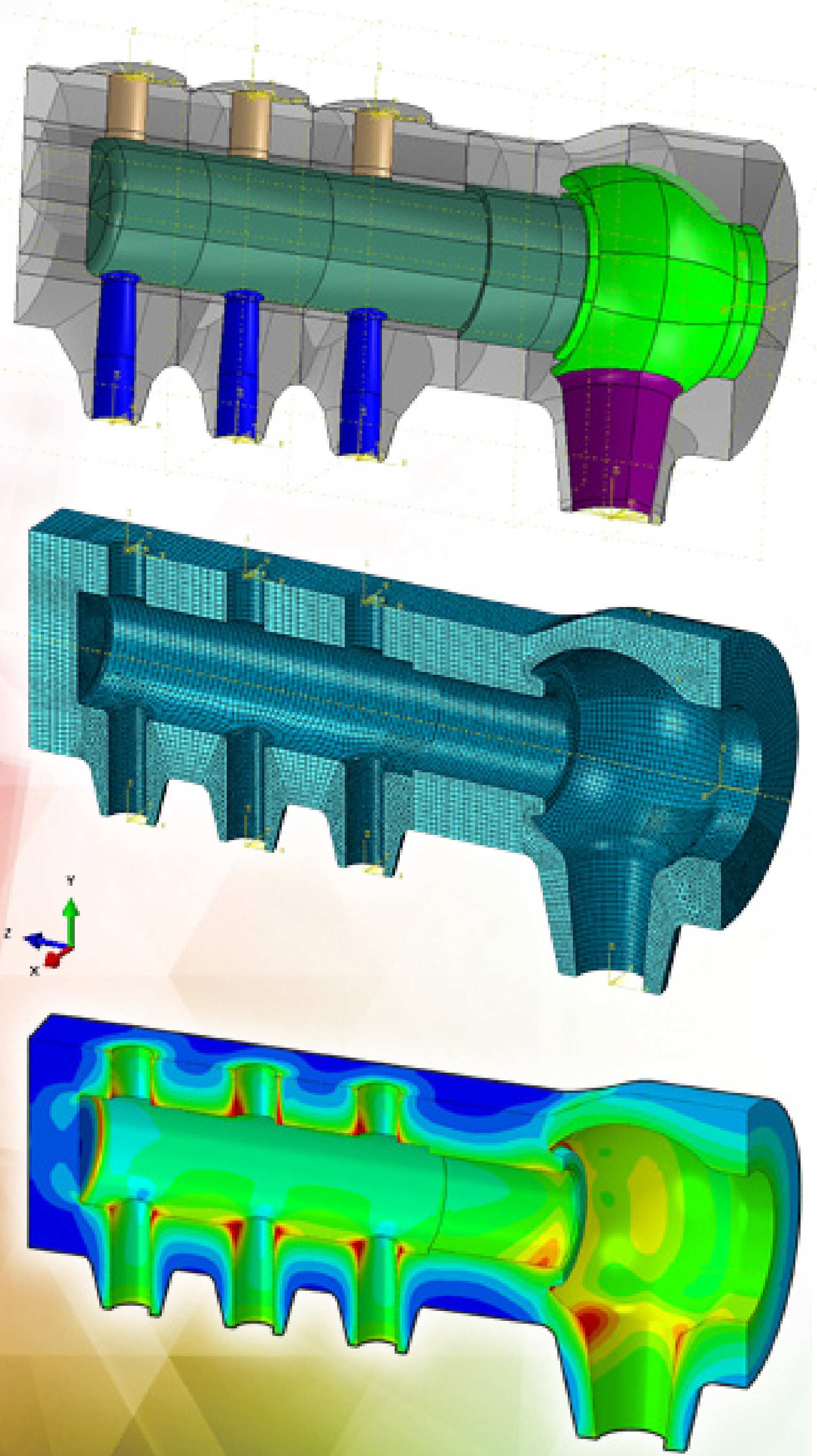
Steam Chest from Top (insulation covering portion of throttle valve end)

THE ROLE OF ADVANCED ANALYSIS IN EQUIPMENT LIFE CYCLE MANAGEMENT CONTINUED

some conservatism was included in the assumed operating heating/cooling rates due to incomplete historical data.

Fracture mechanics calculations were also performed to establish maximum allowable flaw sizes and to evaluate the rate of creep and fatigue crack growth assuming the presence of existing cracks. These calculations are important for understanding flaw tolerance and the time for flaws to progress to substantial size where they limit structural integrity. The results are used for establishing future inspection timing or planned repairs, as necessary. In this particular case, the rate of crack growth due to thermal fatigue was rapid near the surface, but the driving force decays rapidly through the wall thickness, requiring on the order of 30 years for an assumed initial crack depth of 1/8 to double in size.

The scope of the inspection performed on site was somewhat limited based on the outage schedule, but did not result in identifying any surface cracking. Based on the analysis results and limited extent of prior inspections, a plan for confirmatory targeted detailed surface and volumetric examination was recommended for the next outage. Assuming no anomalies are discovered, subsequent inspection intervals would then be extended based on the supporting engineering analysis.



DEEPWATER OFFSHORE EQUIPMENT BENEFIT FROM FATIGUE LOAD MONITORING IN CHALLENGING HPHT CONDITIONS

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In this article, we'll share with you how we are using validated and reliable processes, procedures and software that we developed 30 years ago for application in the nuclear sector for the Load Monitoring of critical equipment used in the high pressure, high temperature (HPHT) oil and gas industry, and how we're directly applying these methods to deep offshore well head equipment. We'll also share some of the results and insights we've gained in recent HPHT applications. Those of you who have implemented Structural Integrity's FatiguePro™ software in your nuclear plants will likely recognize some familiar benefits that can be realized in HPHT equipment.

Oil and gas operators view deepwater installations as the primary source of significant future discoveries of oil and gas reserves. The challenge facing the industry is that the environments for such installations present design conditions for which proven American Petroleum Institute (API) pressure rating designs are not yet available. These applications reside in ocean water that may be more than a mile deep, and the equipment is exposed to internal sour environments at pressures greater than 15,000 psig and temperatures greater than 350°F, while surrounded by near freezing ocean water (Figure 1). To further complicate design, such high pressures require thick-walled equipment that are designed to ASME Code, Section VIII and API standards; but, these emerging pressure and temperature extremes are beyond what API standards currently address. These conditions provide technical challenges to components not previously seen by in-service equipment. Inside surface initiated fatigue cracking, not previously considered a likely threat in earlier subsea applications, has a greater potential to be an influencing integrity threat in these very thick-walled components.

Using our FatiguePro™ 4 software, coupled with our in-house API and ASME Code expertise, we have developed a methodology for load monitoring and fatigue management for thick-walled, nickel-lined forgings subjected to these harsh conditions that can be applied in any HPHT application by any knowledgeable engineer. FatiguePro™ 4 uses reliable technology that has been validated over

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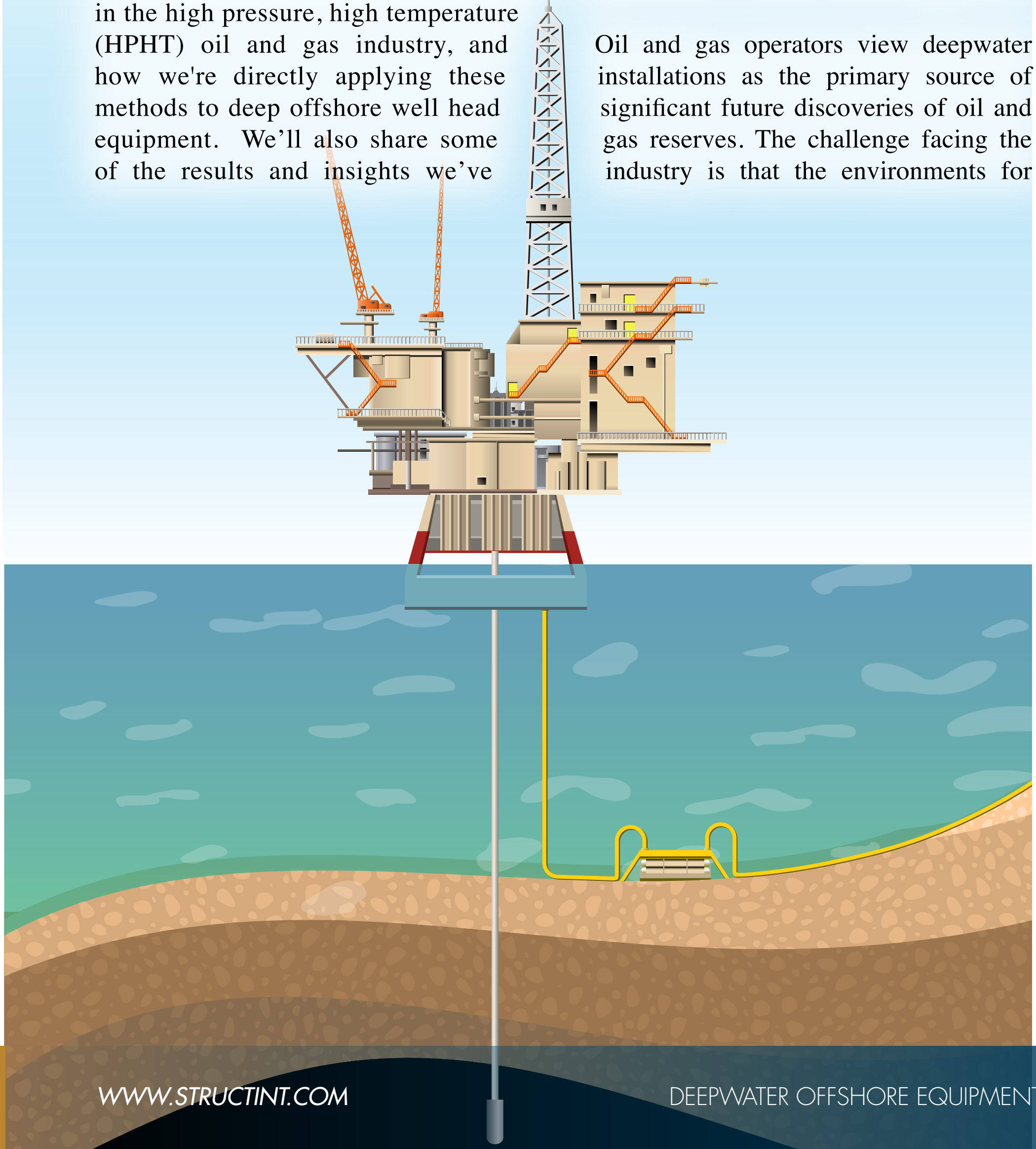


Figure 1. Schematic of a Deep Sea HPHT Installation

DEEPWATER OFFSHORE EQUIPMENT BENEFIT FROM FATIGUE LOAD MONITORING…CONTINUED

High-pressure High-temperature
Design Guidelines

DRAFT

Figure 2. Revised API Technical Report

several decades of successful wide-spread use since its development in 1986 for application in the commercial nuclear power sector. In addition, we have shared our expertise with the API community by volunteering as authors of the Load Monitoring Annex A in the new API Technical Report 17TR8, Revision 2, which is currently being finalized for publication (Figure 2).

Although fatigue has traditionally not been a concern for deep sea well head equipment, small imperfections in the material and continuous exposure to the sour environment, coupled with extreme pressure and temperature fluctuations, increase the potential for fatigue damage in the form of crack initiation and environmentally-enhanced crack growth. In addition, standard equipment design practices that used stress concentrations for lower-pressure well equipment now estimate very large stresses in the high-pressure well head equipment. Subsequent growth and penetration of these small fatigue cracks through the corrosion resistant interior layer into the forging base material could then result in through-wall crack propagation, ultimately leading to leaks, which could be environmentally disastrous. Unfortunately, the location and assembly of these subsea components do not readily lend themselves to in-service nondestructive examination (NDE) after deployment. As a result, load and/or fatigue monitoring becomes a necessary engineering solution. Load monitoring with FatiguePro™ 4 provides a way to consistently and constantly monitor the condition of equipment to alert the operator before a critical condition threatens component integrity.

FatiguePro™ 4 provides load monitoring of critical locations in subsea equipment – in essence, a “fatigue and load odometer” for equipment “hot spots” that serve as leading indicators of fatigue. We do this by strategically pairing, counting, categorizing, and tracking all of the actual loads to which the equipment is exposed in a more rigorous method than simply counting the extreme minimums and maximums. (Figure 3). Once the actual unique loading history is identified, it may be compared to loadings assumed in the design, or fatigue crack initiation and growth parameters may be calculated for comparison to allowable values or alarm limits. The key locations selected for sentinel monitoring are readily determined from the finite element analysis (FEA) performed as part of the ASME Code, Section VIII design analysis (Figure 4).

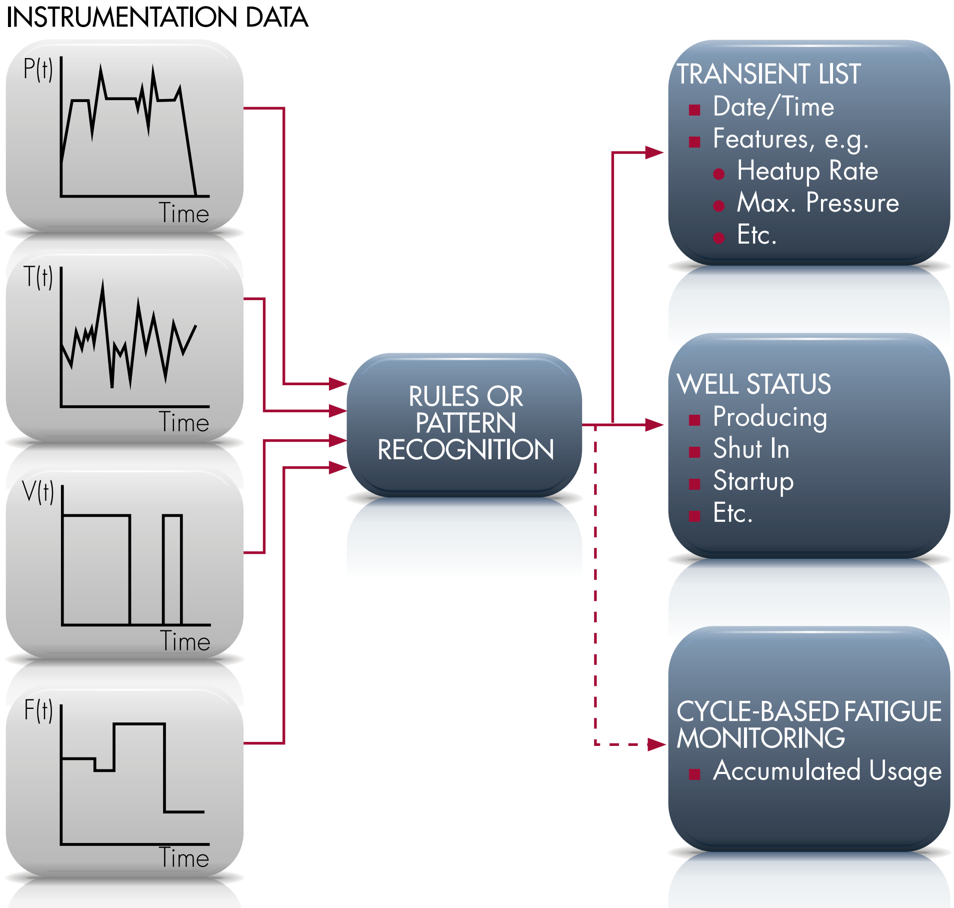


Figure 3. Counting and Categorizing Loads

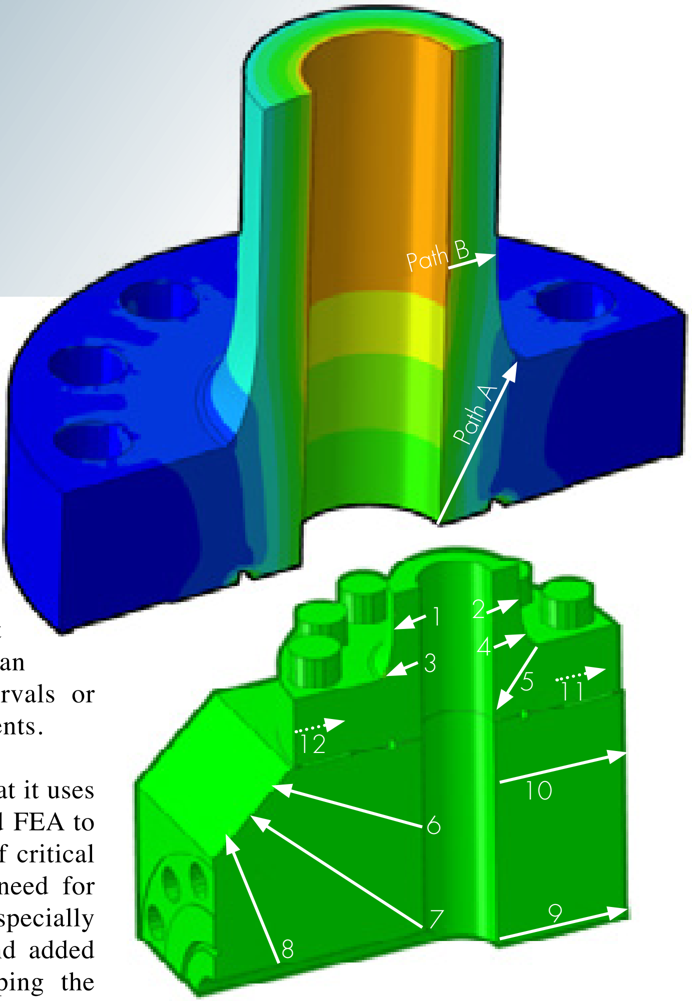
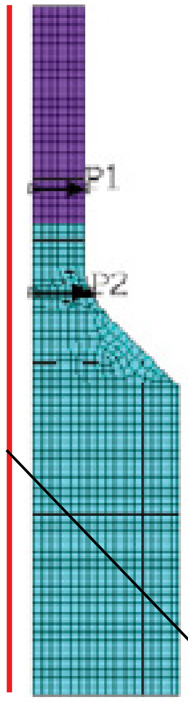


Figure 4. Finite Element Model and Critical Location Selection



We identify locations of highest stress, including the effects of structural or material discontinuities, through the modelling process and selected for monitoring in FatiguePro™ 4. We configure the software to utilize all of the same methods and inputs that are used to qualify the equipment to ASME standards. However, actual loading measured from installed instruments is used in place of design assumptions for loading, thus providing in-situ measurement and assessment of the actual component duty. The analysis can be performed remotely onshore at regular intervals or immediately updated after unusual operational events.

A key feature of our FatiguePro™ 4 software is that it uses existing instrumentation and previously developed FEA to provide remote and continuous load monitoring of critical well head equipment. This feature avoids the need for costly installation of additional instrumentation, especially in cases where routing of remote instruments and added electrical cabling may be cost-prohibitive, keeping the implementation cost of this solution low. The key to this approach is the use of Green's Functions and transfer function logic, which provide mathematical modelling of available instrument measurements and their relationship to conditions at the monitored location of interest (Figure 5). Such modelling provides for a "virtual instrument" – that is, predicted measurements of pressure and temperature at the critical monitored location of interest as if there were instruments installed at that location (Figure 6). The technique, used also in nuclear power, can be applied as early as the design stage, or once a component has entered service.

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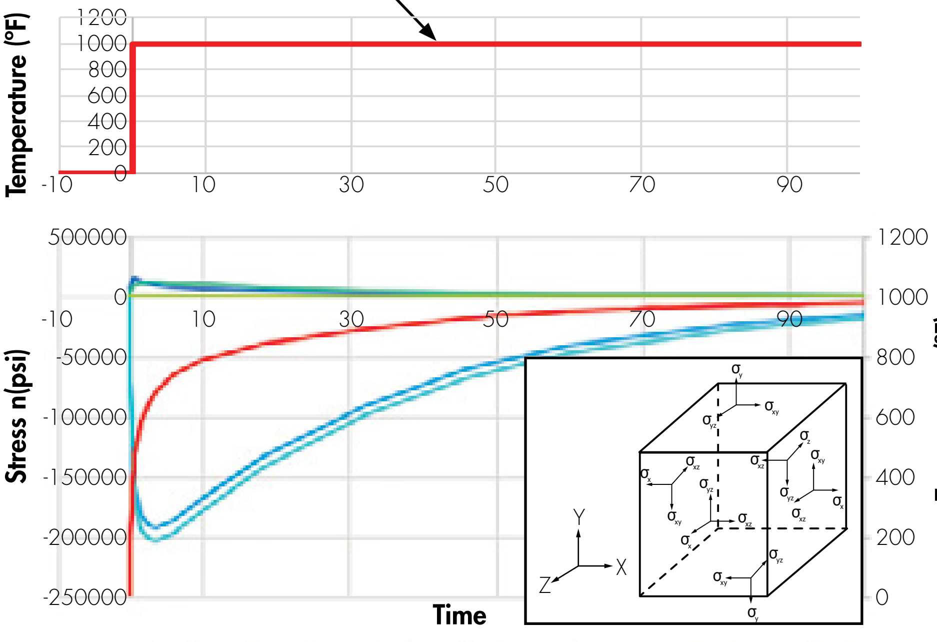


Figure 5. Use of Green's and Transfer Functions

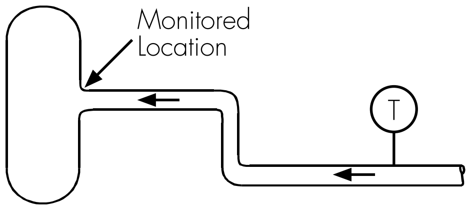


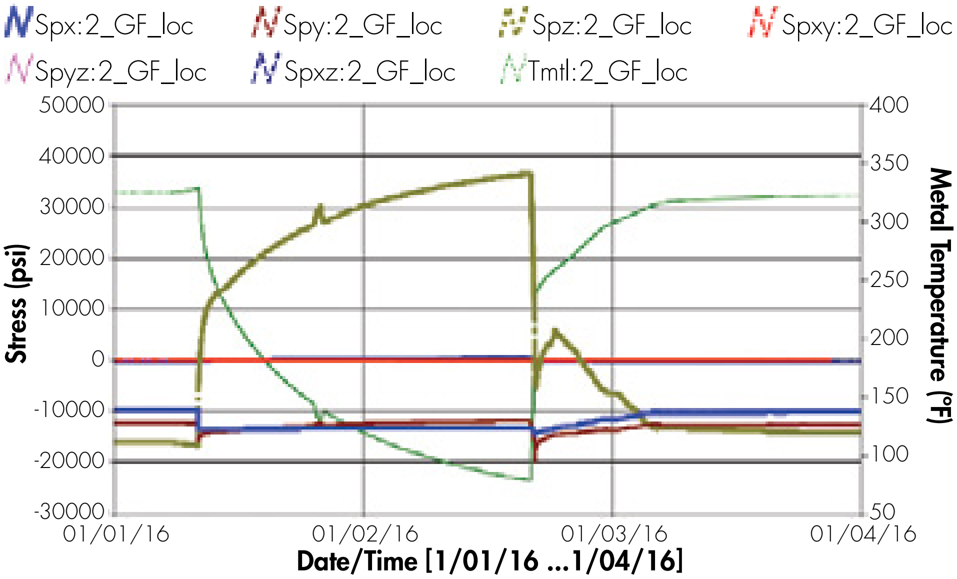
Figure 6. Virtual Instrument Concept

DEEPWATER OFFSHORE EQUIPMENT BENEFIT FROM FATIGUE LOAD MONITORING…CONTINUED

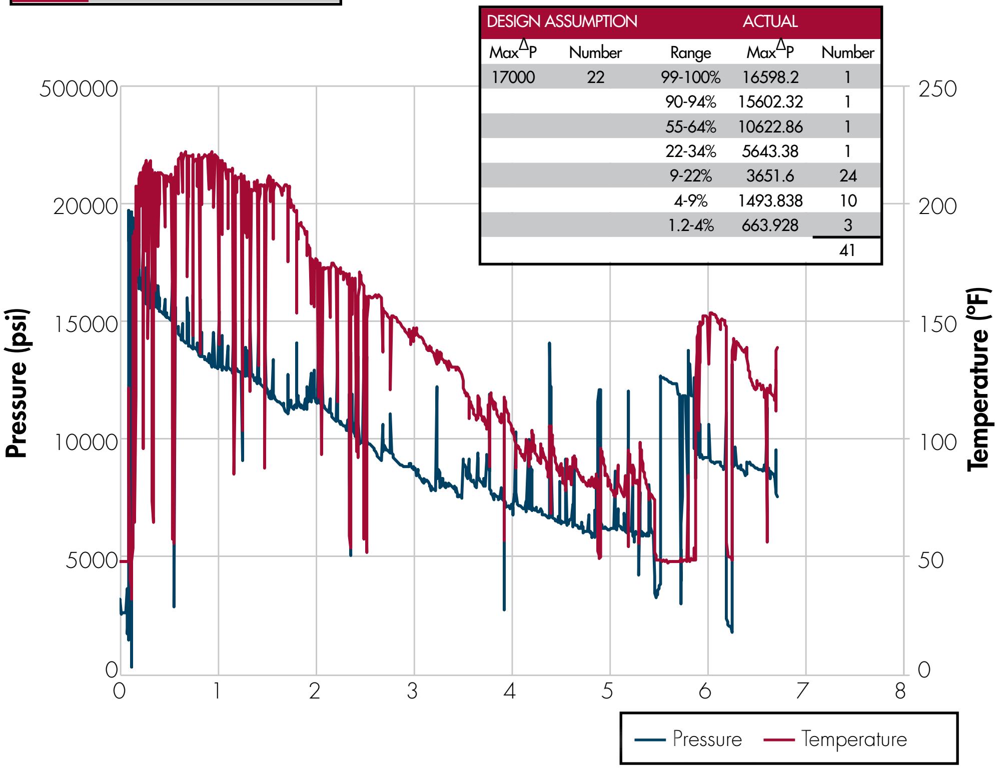
FatiguePro™ 4 analyses all use measured fluctuations of pressure and temperature, or other available measured loads. Those fluctuations are identified, counted and categorized according to severity for direct comparison to the loads postulated in the equipment Design Specification. This comparison can serve as a first-level measure of the equipment's condition, in that the loading is measured and compared against its accepted, benchmarked design standard.

A typical field observation for most equipment is that the actual field loading is much less severe than the loading postulated in the design of the equipment (Figure 7). Accounting for this difference can extend the equipment's life, oftentimes significantly – but more importantly, provide the added level of confidence in the safety and reliability of the equipment. Using the Green's and transfer functions, FatiguePro™ 4 may also be used to calculate both a cumulative usage factor (cuf) as a measure of fatigue crack initiation or postulated fatigue crack growth (Figue 8). Both of these parameters can be plotted real-time and trended into the future to provide insight to operational practices, equipment maintenance or for proactive planning of equipment replacement (Figure 9). Alert levels can be set to trigger other proactive measures by operators long before problems are encountered.

Our FatiguePro™ 4 software also provides evaluation of both past and future "what-if" operational practices to show the results of planned or desired operational improvements. This provides important feedback to operators ahead of time that allows for procedure adjustment or the avoidance of operating practices that can prematurely consume equipment operational life.



TYPE	S_{alt}(KSI)	N_{allow}	MARGIN
ACTUAL	30.4	21336.92	5.9
DESIGN	53.2	3609.90	



DESIGN ASSUMPTION		ACTUAL		
MaxΔP	Number	Range	MaxΔP	Number
17000	22	99-100%	16598.2	1
		90-94%	15602.32	1
		55-64%	10622.86	1
		22-34%	5643.38	1
		9-22%	3651.6	24
		4-9%	1493.838	10
		1.2-4%	663.928	3
				41

Figure 7. Actual Data and Comparison to Design
(Top Plot: comparison of temperature and pressure loading; Bottom plot: comparison of allowable fatigue cycles based on stress evaluation)

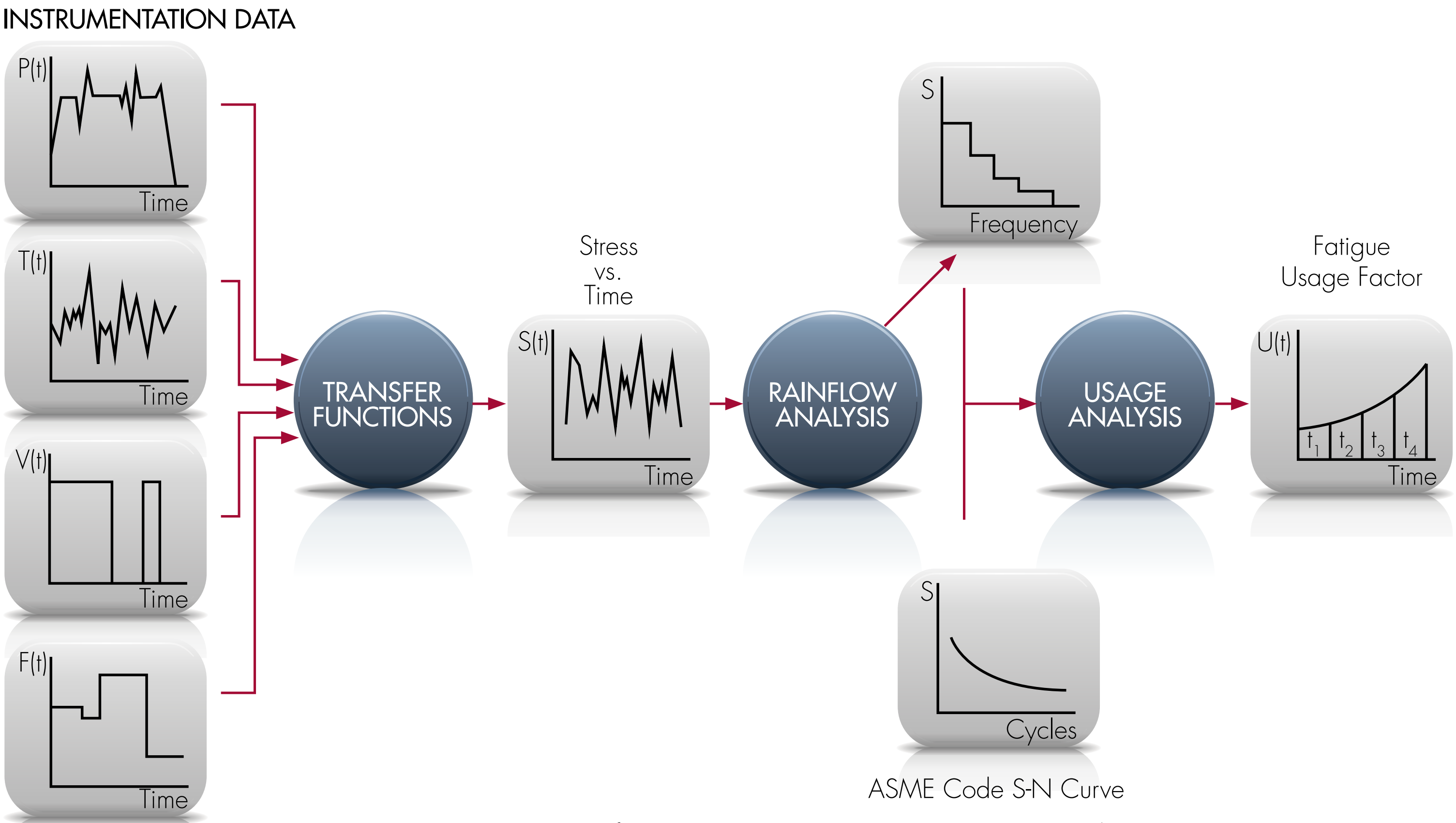


Figure 8. Result of Using Green's Functions to Determine Available Margin

Our FatiguePro™ 4 computational fatigue analysis software integrates both FEA and fracture mechanics to establish improved fatigue tolerance and fatigue life cycle management during operation. Implementing this methodology will also provide key technical data that can be used to improve future well completion designs. Properly understanding the influence and effects of HPHT environments on new-generation equipment can result in significant weight and cost savings.

To learn more about FatiguePro™ 4 and its application to your well head equipment, or to partner with us on load monitoring applications, contact us at **1-877-4SI-POWER**.

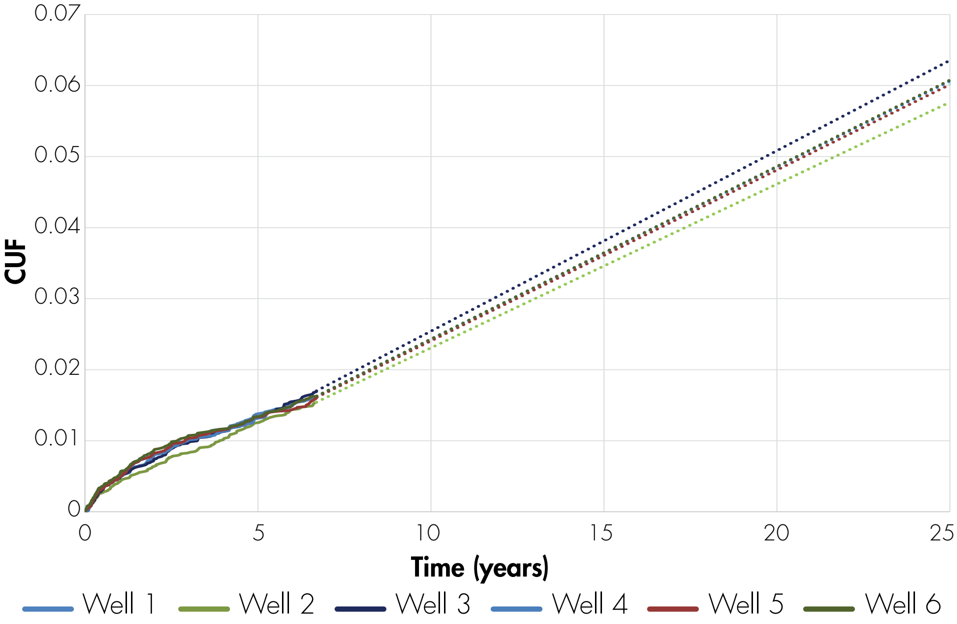
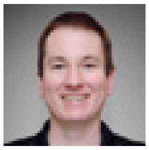


Figure 9. Trending and Extrapolating Component Life

USE OF 3-D FLUENCE MODELS FOR CORE BARREL FLAW TOLERANCE



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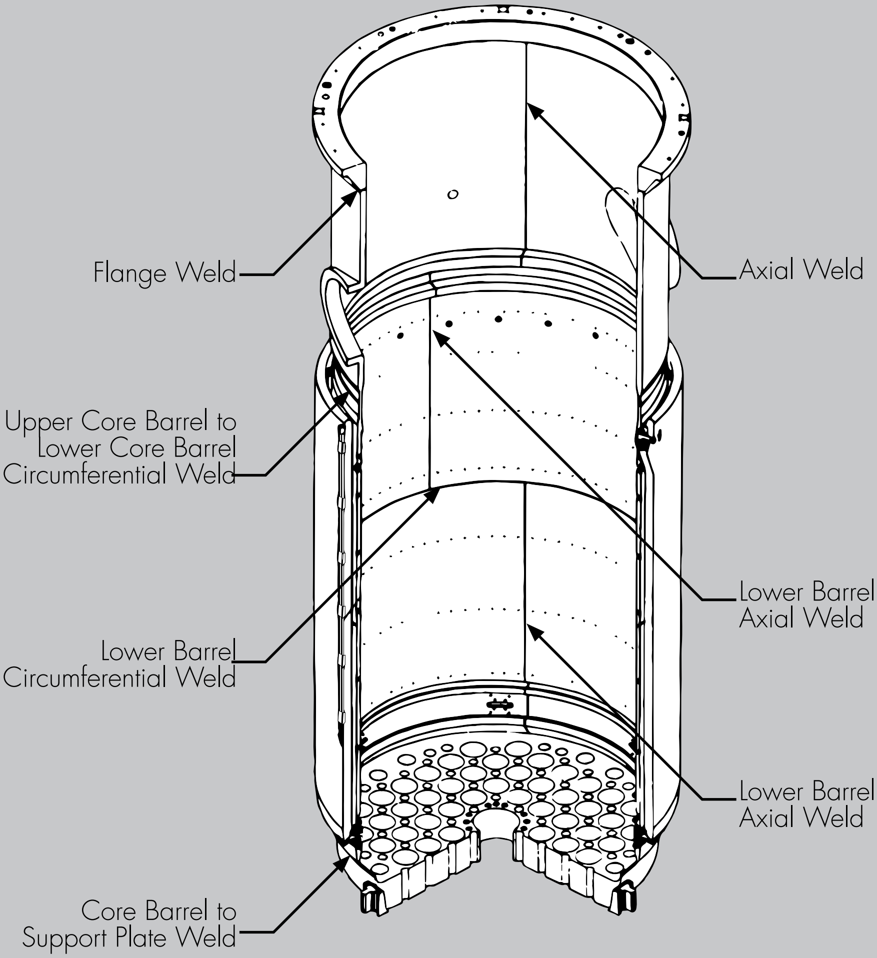
The industry is well aware of the significance of determining radiation damage to a reactor pressure vessel. Determining aging, with a focus on neutron fluence, in reactor vessels is a requirement that must be addressed with the Nuclear Regulatory Commission (NRC) as part of the licensing process for a nuclear reactor. To address this important issue, the NRC issued several regulatory guides that describe the requirements for fluence evaluations and provide guidance for how fluence must be determined and used to evaluate vessel integrity. We acknowledge that the design bases for the world's fleet of nuclear reactors assumed a maximum 40-year operating life, and that most design basis analyses demonstrated the adequacy for those designs. However, the industry is breathing new life into those aging plants by seeking operating licenses to 60 years, and very soon to 80 years. As a consequence, new analyses are being required, not only by the NRC, but the owners/operators of the plants to determine if the existing fleet of reactors, their pressure vessels, and vessel internals can meet the new demands for extended life operation.

Figure 1. Major fabrication welds in typical Westinghouse core barrel



Understanding that reactor internals are susceptible to age-related degradation due to radiation damage, monitoring programs must be established to manage these internals for plant license renewal. One of the key components for pressurized water reactors that must be considered in the internals management process is the core barrel. A typical core barrel design is shown in Figure 1 (above). The regions to be inspected on the core barrel per MRP-227-A include the lower barrel circumferential weld that is in the high fluence area adjacent to the reactor core. In preparing for an inspection outage, utilities would like to have a flaw handbook identifying existing flaw locations and the characteristics about the flaw, along with maximum allowable flaw sizes in the event that new indications may be found. If new indications are found, it is also desirable to have detailed and accurate fluence information for the circumferential and vertical welds in the barrel so that new indications can be thoroughly assessed. Having the capability to quickly assess and disposition new indications may also assist in reducing outage time, resulting in a cost savings that could also contribute to the utilities commitment to delivering the nuclear promise.

Flaw evaluation procedures for the core barrel welds are described in WCAP-17096-NP. The WCAP indicates that a fluence estimate at the flaw location is required for all flaws in the RPV beltline (i.e., high fluence) region. When a flaw is detected, it is essential to know enough about the material properties to be able to establish the failure mode. In addition to the specific design and stress levels, the fluence in the component has a large bearing on the maximum allowable flaw lengths. This is because fluence accumulation changes the properties of the core barrel materials from high toughness to low toughness with increasing fluence. Per MRP-227-A, for neutron fluence less than 0.5 dpa ($3.5x10^{20}$ n/cm^2), only a Limit Load (LL) evaluation is needed in order to determine the continued service of the internals assembly or individual component. For neutron fluence above 0.5 dpa ($3.5x10^{20}$ n/cm^2) and below 5 dpa ($3.5x10^{21}$ n/cm^2), an Elastic-Plastic Fracture Mechanics (EPFM) evaluation is the appropriate method, but a Linear Elastic Fracture Mechanics (LEFM) evaluation can be used. For neutron fluence above 5 dpa ($3.5x10^{21}$ n/cm^2), an LEFM evaluation should be used.

The fluence threshold limits on the use of different methodologies is summarized below:

Limit Load	fluence ≤ 0.5 dpa ($3.5x10^{20}$ n/cm^2)
EPFM (preferred) or LEFM	0.5 dpa ($3.5x10^{20}$ n/cm^2) < fluence ≤ 5 dpa ($3.5x10^{21}$ n/cm^2)
LEFM	fluence > 5 dpa($3.5x10^{21}$ n/cm^2)

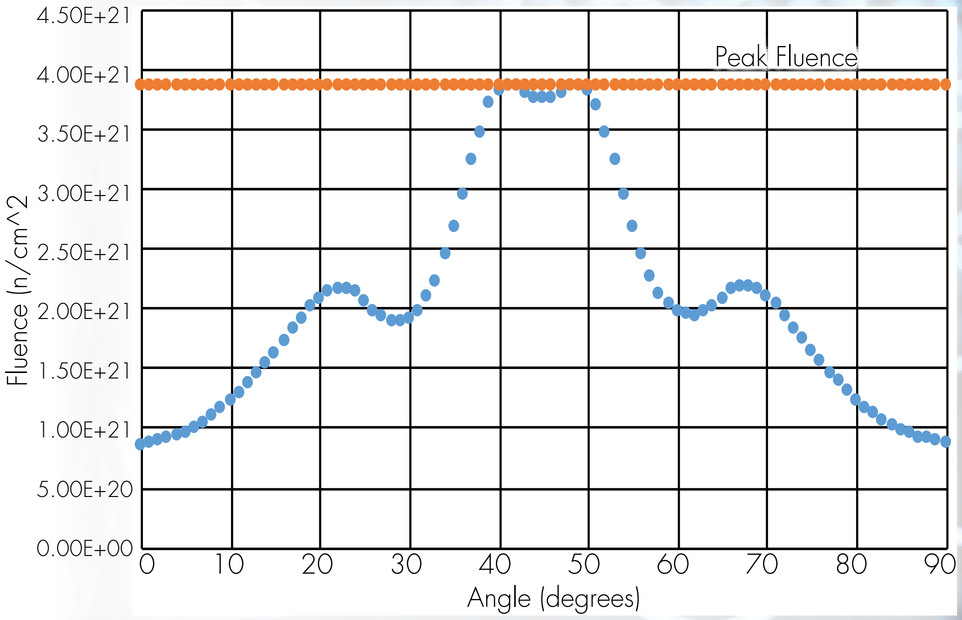
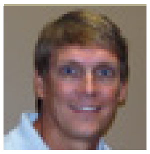


Figure 2. Calculated fluence in the core barrel

The three different methods can lead to large differences in the allowable flaw size for the same loadings. In order to avoid excess conservatism in the calculation of allowable flaw sizes, a more detailed fluence evaluation of the core barrel may be needed. Many plants still use simple two-dimensional (2-D) fluence calculations, coupled by a synthesis method to determine a bounding peak fluence for the core barrel weld. A true 3-D fluence calculation will give more detailed and more accurate best-estimate fluence value at all azimuths and elevations of the core barrel. A comparison of a bounding 2-D peak fluence versus a true 3-D best-estimate of the circumferential distribution of fluence at the core barrel weld for 55 EFPY is shown in Figure 2 (right) for a representative PWR plant. As shown in the figure, the fluence varies significantly around the circumference. If a flaw is determined at anything other than the actual peak location, the fluence can be greatly over-predicted using a 2-D method, and require the use of more limiting analyses.

As shown in Figure 2, the bounding peak fluence in the core barrel is above the LEFM threshold. Moving away from this local azimuth, the actual fluence around the core barrel drops below the LEFM ($3.5x10^{21}$ n/cm^2) threshold into the EPFM range. Using representative stress values for the core barrel, allowable through-wall circumferential flaw sizes were evaluated using both the EPFM and LEFM methods. The allowable flaw size for a fluence of ~$2.0x10^{21}$ n/cm^2 using EPFM techniques would allow flaws of approximately 140 inches. If the peak fluence were used, which is approximately $4.0x10^{21}$ n/cm2, with the same stresses, the allowable flaw size would be appreciably reduced to 11 inches long. Using LEFM produces a flaw size that is over ten times smaller than the EPFM approach. This is a substantial difference and shows that using a peak fluence approach can lead to allowable flaw sizes that are much smaller than if a true 3-D fluence approach were used.

With such detailed factors involved, it's important to have experts oversee and evaluate the results.



By: CLARK MCDONALD, PhD
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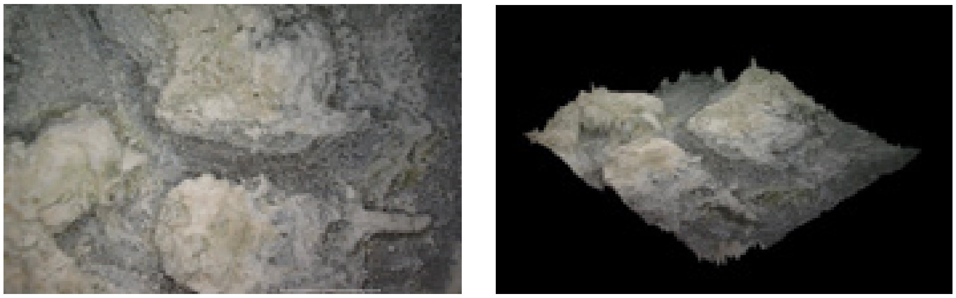
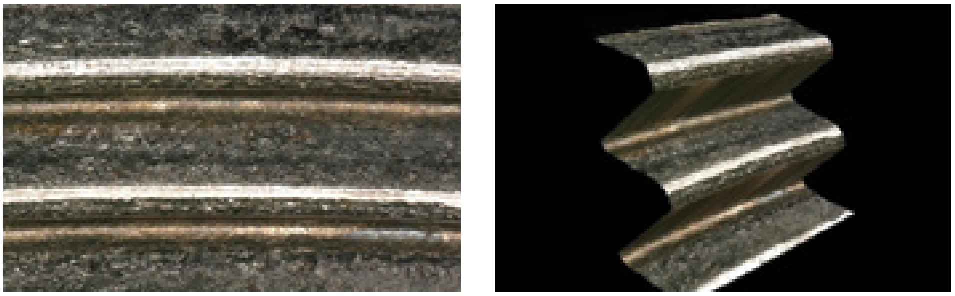
Applications & Benefits of Optical Microscopy

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

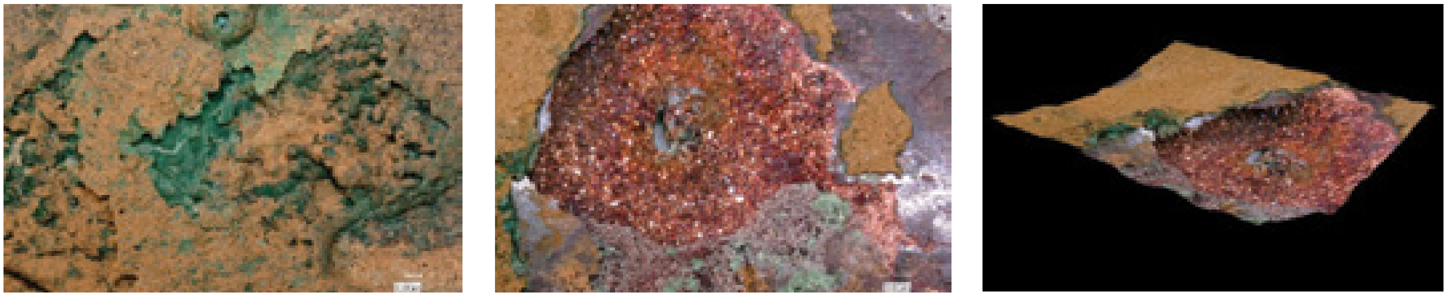
In this edition of Structural Integrity's Lab Corner, we wanted to provide some interesting content related to that middle-of-the-road region of magnification; closer than macro-photography but farther away than the 100X to 5000X magnifications that cover most of the applications requiring scanning electron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



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

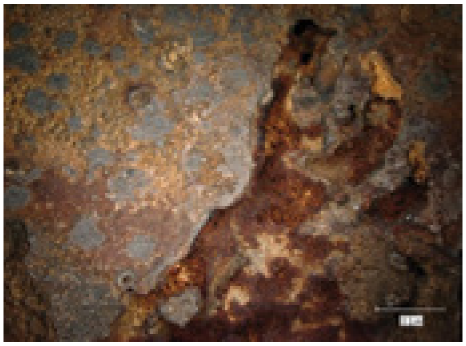


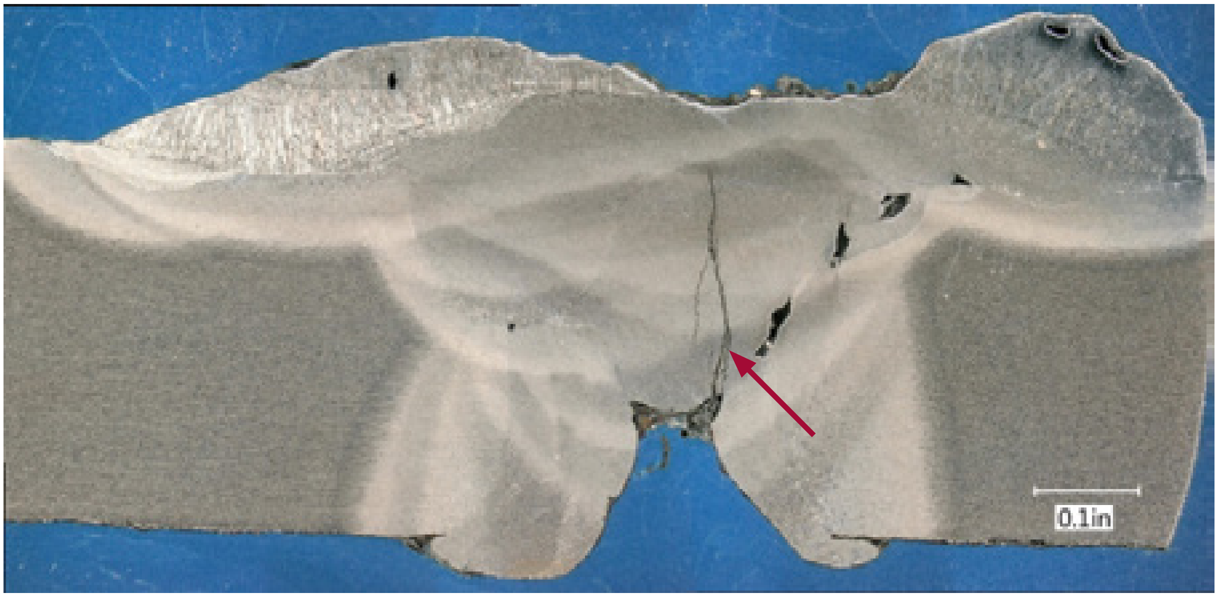
Two- and three-dimensional color images showing fastener thread flank damage and a crack origin near the root of the upper thread. The 3D image shows that the crack origin is located on the thread flank rather than at the deepest part of the thread root.



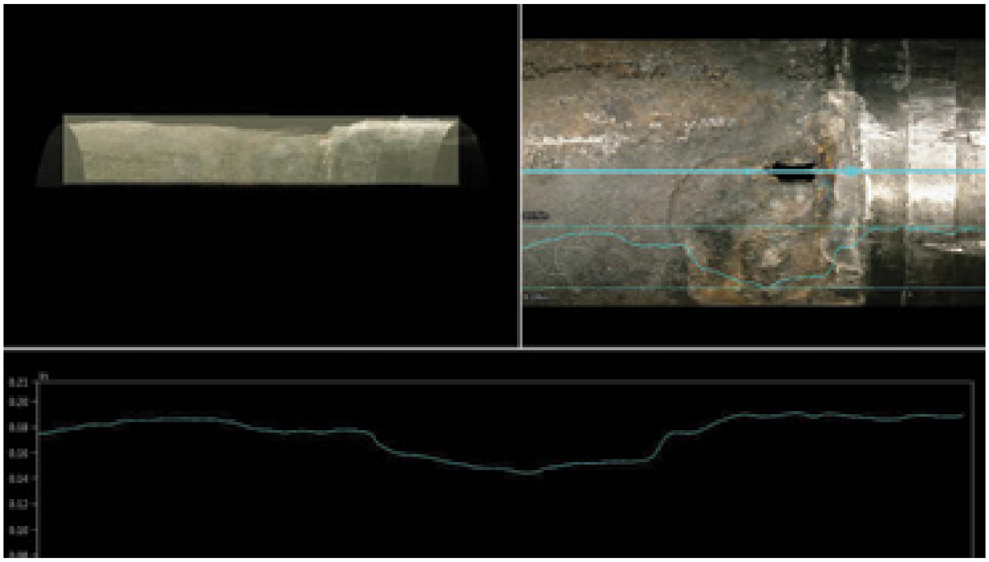
Two- and three-dimensional images of a copper heat exchanger tube that has been damaged from under-deposit corrosion (UDC). The image at left shows the typical appearance of the ID deposits. The center image shows a region of damage surrounding a pinhole leak. The 3D image provides an idea of the depth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

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





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



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

Featured Damage Mechanism - Caustic Gouging

By: WENDY WEISS
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Caustic gouging (CG) is an underdeposit corrosion (UDC) mechanism that has increased in frequency in recent years at some fossil plant boilers and combined cycle plants with heat recovery steam generators (HRSGs). Caustic gouging occurs in the presence of heavy tube deposits and sodium hydroxide that concentrates at the tube surface.

MECHANISM

Caustic gouging requires a buildup of internal deposits along with a concentration of contaminant. The contaminant in this case is sodium hydroxide. Damage begins with the transfer and deposition of corrosion products in the boiler. Thermal-hydraulic conditions increase the concentration of caustic in the deposits. This concentrated caustic dissolves the protective magnetite layer, which leads to the formation of sodium iron oxides (sodium ferroate and sodium ferroite). The corrosion rate increases and final failure occurs when the reduced tube wall thickness can no longer support the internal pressure.

TYPICAL LOCATIONS

- ID surface of hot side of tubes
- Highest heat flux areas
- Near flow disruptors: joints, bends, protruding welds, etc.

FEATURES

- Waterside mechanism
- Pinhole leak or thin-edged failure
- Gouging on ID surface
- Thick adherent deposits within gouge
- Needle shaped deposits within gouge (Crystals of sodium ferroate or sodium ferroite)
- Sodium detected at base of gouge
- No microstructural changes

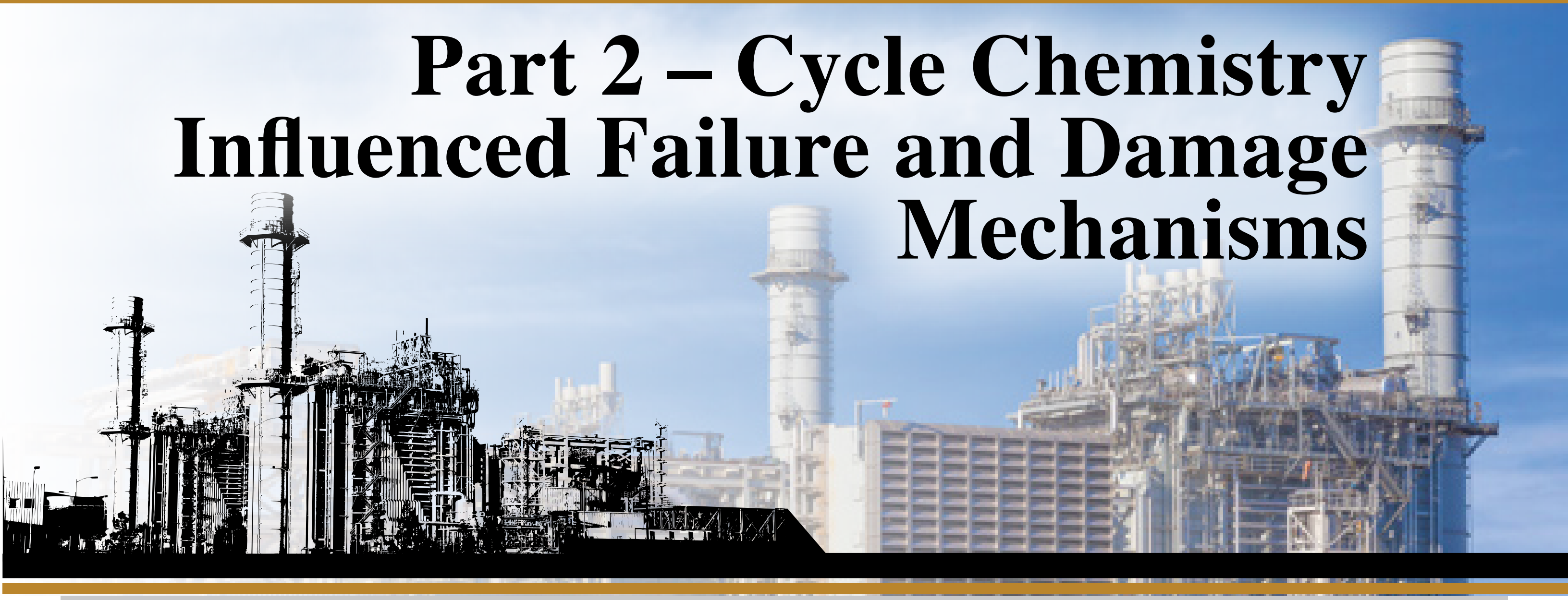
Heavy deposits on ID surface

Gouge on ID surface near bend

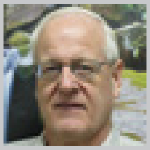
Cross-section through gouge on ID surface

Needle-like Crystals Observed in Caustic Gouging Deposit

CYCLE CHEMISTRY - THE KEY TO RELIABILITY OF FOSSIL AND COMBINED CYCLE/HRSG PLANTS



Part 2 – Cycle Chemistry Influenced Failure and Damage Mechanisms



By: BARRY DOOLEY
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The cycle chemistry treatments and control on fossil and combined cycle plants influence a high percentage of the availability, reliability and safety issues experienced on these plants worldwide. As this is a very large and important area for fossil and combined cycle plants, Structural Integrity decided to describe it in three parts. The first part introduced the equipment and materials of construction and how reliability depends on various protective oxides, the formation of which relates directly to the cycle chemistry treatments that are used in the condensate, feedwater, boiler / HRSG evaporator water, and steam. This second part will delineate the damage and failure mechanisms influenced by not operating with the optimum treatments when the protective oxides break down. The third article will describe the key analytical tools which we developed to identify whether these failure and damage mechanisms will occur by identifying the number of Repeat Cycle Chemistry Situations (RCCS).

1.1 MAJOR CYCLE CHEMISTRY INFLUENCED DAMAGE/FAILURE IN FOSSIL AND COMBINED CYCLE/HRSG PLANTS

1.1.1 OVERVIEW OF CYCLE CHEMISTRY INFLUENCED DAMAGE/FAILURE MECHANISMS

It is not surprising that because the cycle chemistry "touches" all the parts of a generating plant that it controls the availability and reliability of these plants. It has been suggested over the last 10-20 years that the cycle chemistry influences about 50% of all the failure and damage mechanisms in conventional fossil plants, and because of the added complexity of combined cycle / HRSG plants with multiple pressures this number may be as high as 70%. The statistics of cycle chemistry influenced failure and damage mechanisms in conventional fossil and HRSG plants have changed very little over the last 25 years or more. These can be categorized as follows:

- Boiler Tube Failures in Fossil Plants
  - Under-deposit Corrosion (UDC) (mainly hydrogen damage with acid phosphate corrosion and caustic gouging occurring less frequently)
  - Corrosion Fatigue in sub-critical waterwall tubes and supply piping
  - Thermal fatigue in waterwalls due to internal deposits (particularly, but not exclusively, in supercritical boilers)
  - Pitting in reheaters, superheaters and economizers
- HRSG Tube Failures
  - FAC in LP and IP Evaporators, LP, IP and HP economizers (single- and two-phase)
  - Corrosion Fatigue in LP Evaporators and Economizers
  - Under-deposit Corrosion (UDC) in HP evaporators of both vertical and horizontal gas path HRSGs (mainly hydrogen damage but acid phosphate corrosion and caustic gouging have also occurred)

Continued on next page

CYCLE CHEMISTRY - THE KEY TO RELIABILITY OF FOSSIL AND COMBINED CYCLE/HRSG PLANTS CONTINUED

  - Pitting (often evidenced as tubercles in pressure vessels (drums, deaerators))

- FAC in Conventional fossil feedwater systems (from condensate pump discharge to economizer inlet)
  - Single- and two-phase

- FAC in Air-cooled Condensers (with main damage by two-phase FAC and Liquid Droplet Impingement at ACC tube entries in upper ducts)

- Steam Turbine Damage
  - Corrosion Fatigue of blades and disks in the Phase Transition Zone (PTZ) of the LP Turbine
  - Stress Corrosion Cracking of blades and disks in the PTZ of the LP Turbine
  - Pitting
  - Copper Deposition in HP Turbine
  - Flow-accelerated Corrosion (FAC)
  - Deposition of Salts on the PTZ Surfaces

It is important to note that although FAC and UDC mechanisms occur at opposite ends of the fossil and combined cycle / HRSG plants, they are linked by the corrosion products generated by the corrosion and FAC mechanisms in the fossil feedwater systems and the low pressure parts of the HSRG respectively. These corrosion products subsequently transport to, and deposit in, the fossil waterwalls and HRSG HP evaporator tubing where they form the basis of the under-deposit corrosion damage mechanisms. This link forms the main focus of cycle chemistry assessments in fossil and HRSG plants, which identify the precursors or active processes, which left unaddressed, will eventually lead to failure / damage by one or both mechanisms. Acting proactively will remove the risk for both, and it is clear that avoiding FAC is an essential part of ensuring that UDC will not occur.

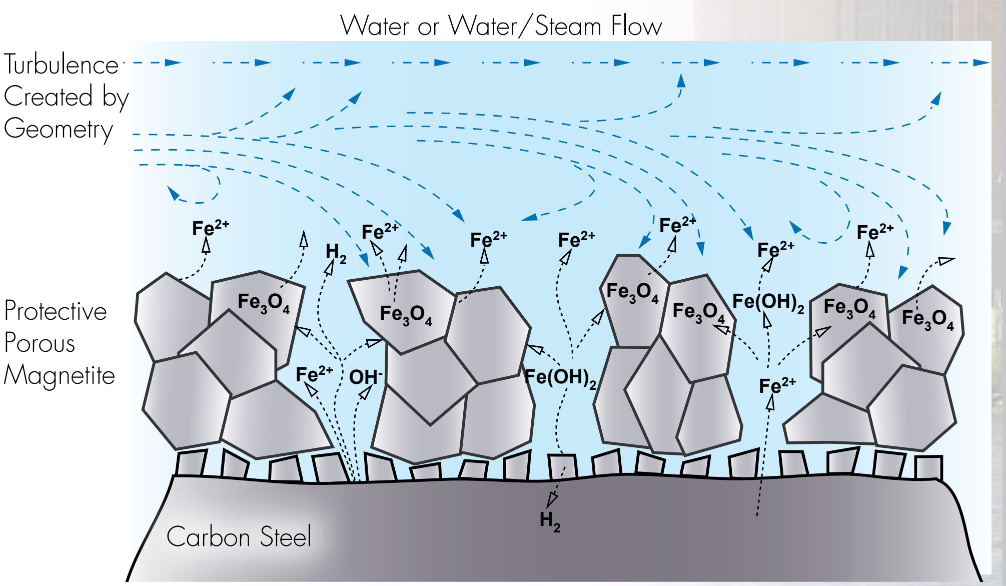


Figure 1: Schematic of FAC mechanism [Source: R.B. Dooley, *Flow-Accelerated Corrosion in Fossil and Combined Cycle/HRSG Plants*, PowerPlant Chemistry, 2008, 10(2), pp 68-89]

Because of the vast array of publications on cycle chemistry influenced failures and damage which is available in the literature there is only time in this Part 2 article to provide a few abbreviated examples of the mechanisms of FAC, UDC and deposition, and of phase transition zone damage in the steam turbine.

1.1.2 FLOW-ACCELERATED CORROSION (FAC) IN FOSSIL AND COMBINED CYCLE / HRSG PLANTS

The mechanism of FAC is the same in both plants but the location of damage is different. In fossil plants FAC predominates in the feedwater systems whereas in combined cycle plants it is primarily located in the low pressure / temperature circuits of the HRSG. FAC involves the accelerated dissolution of the protective oxide (magnetite) on the surface of carbon steel components caused by flow and the mechanism is illustrated in Figure 1.

FAC in Combined Cycle / HRSGs. All the HRSG components within the temperature range (212 - 572°F, 100 - 300°C) are susceptible to FAC which involves both the single- and two-phase variants predominantly in low temperature (LP, IP and HP) economizers / preheaters and evaporators (tubes, headers, risers and drum components such as belly plates). The same components can

also be susceptible to FAC in HRSG designs where the nominal HP evaporator circuit operates for significant periods of time at temperatures < 572°F (300°C); for example, the HP evaporators in older dual-pressure HRSGs, HRSGs where there is only one pressure stage, and high pressure evaporator circuits in plants running for extended periods at low load with sliding pressure operation. A quite comprehensive listing of locations of FAC in combined cycle / HRSGs is provided in Table 1 below.

Table 1. Locations of FAC in Combined Cycle / HRSG Plants

- LP Economizer / preheater (feedwater) tubes at inlet headers (SA 178A, SA 192, and SA 210C tubing; SA 106B headers; 105-300°F, 40-150°C)
- Economizer/preheater tube bends in regions where steaming takes place with particular emphasis being given to the bends closest to the outlet header (SA 178A, SA 192, and SA 210C tubing; SA 106B headers, 105-300°F, 40-150°C)
- IP/LP economizer outlet tubes (SA 178A, SA192, SA 210C tubing; SA 106B headers; 260-300°F, 130-150°C)
- HP economizers tube bends in regions where steaming takes place with particular emphasis being given to the bends closest to the outlet (SA 210 A1 and C tubing; ~320°F, 160°C)
- IP and HP economizer inlet headers (SA 106B; 140-210°F, 60-100°C)
- LP evaporator inlet headers with a contortuous fluid entry path or with any orifices installed (SA 106B; 260-340°F, 130-170°C)
- LP outlet evaporator tubes at bends before the outlet header (SA192, SA 178A and SA 210C; 150-165°C, 300-330°F)
- LP evaporator link pipes and risers (SA 106B, 300-330°F, 150-165°C)
- Horizontal LP evaporator tubes on vertical gas path (VGP) units especially at tight hairpin bends (SA192; 300-300°F, 150-160°C)
- LP and IP drum internals: behind the belly plates in line with riser entry fluid into the drums
- IP economizer outlet tubes with bends (SA178A, SA192, SA 210A1 and C) and headers (SA 106B and C) (410-445°F, 210-230°C) if there is evidence of steaming
- IP evaporator inlet headers (SA 106B) with a contortuous fluid entry path or with any orifices installed (210-250°C, 410-482°F)
- IP outlet evaporator tubes (SA178A, SA192 and SA 210C; 445-465°F, 230-240°C) on triple-pressure units especially if frequently operated at reduced pressure
- IP outlet link pipes and evaporator risers (SA 106B) to the IP drum (445-465°F, 230-240°C)
- Piping around the boiler feed pump. Includes SH and RH desuperheating supply piping
- Reducers on either side of control valves
- Turbine exhaust diffuser
- Air-cooled condenser (see next sub-section)

(Adopted from R.B. Dooley and R.A. Anderson, Assessments of HRSGs – Trends in Cycle Chemistry and Thermal Transient Performance, PowerPlant Chemistry, 2009, 11(3), 132-151)

FAC in Air-cooled Condensers (ACC). An increasing number of plants worldwide are equipped with air-cooled condensers (ACC). Operating units with ACC at relatively low condensate pH (9.0 – 9.4) will result in serious corrosion and FAC in the ACC tubes, most predominantly at the entries to the cooling tubes. The potential for air-cooled condensers (ACC) to act as a major source of corrosion

Continued on next page

products needs to be considered in developing the optimum cycle chemistry control for plants. Whether this is occurring can easily be determined by monitoring the total iron at the condensate pump discharge (CPD). A condensate / feedwater pH of around 9.8 (as measured at 25 °C) will be needed to reduce the FAC to low enough levels to observe total iron values at the CPD of around 5 µg/kg (ppb) or less. Alternatively, a film forming amine product (FFAP) can be used as described in Part 1. Operating with elevated pH and/or an FFAP to control low temperature FAC in the ACC will also assist in addressing two-phase FAC in the other areas of the plant.

The cycle chemistry influenced damage in ACC can be best described through an index for quantitatively defining the internal corrosion status of ACC. This is known by the acronym DHACI (Dooley Howell ACC Corrosion Index). (Source: R.B. Dooley, D. Aspden, A.G. Howell and F. du Preez, *Assessing and Controlling Corrosion in Air-cooled Condensers*, PowerPlant Chemistry 2009, 11(5), 264-274). The index separately describes the lower and upper sections of the ACC. The index provides a number (from 1 to 5) and a letter (from A to C) to respectively describe / rank an ACC following an inspection. For example, an Index of 3C would indicate mild corrosion at the tube entries, but extensive corrosion in the lower ducts.

The DHACI can be used to describe the status of a particular ACC in terms of its corrosion history and is a very useful means of tracking changes that occur as a result of making changes in the cycle chemistry. Additionally, the index provides a convenient tool for comparison between different units worldwide. This can aid in determining whether some cycle chemistry factor in effect at one station, e.g. use of an FFAP rather than ammonia, is yielding better results.

1.1.3 FAILURE / DAMAGE MECHANISMS IN FOSSIL AND HRSG PLANTS: HIGHLIGHTING DEPOSITION AND THE UNDER-DEPOSIT CORROSION (UDC) MECHANISMS

The three UDC mechanisms, hydrogen damage, acid phosphate corrosion and caustic gouging, occur exclusively in fossil waterwall and HRSG HP evaporator tubing, and all require relatively thick porous deposits and a chemical (either a contaminant or non-optimized treatment) concentration mechanism within those deposits. UDC damage can occur early in the life of a plant due to the inverse relationship between deposit loading / thickness and the severity of the chemical excursion.

For hydrogen damage (HD), the concentrating corrodent species is most often chloride which enters the cycle through condenser leakage (especially with seawater or brackish water cooling) and via slippage into demineralized makeup water in water treatment plants where ion exchange resins are regenerated with sulfuric or hydrochloric acid. (Source: R.B. Dooley and A. Bursik, *Hydrogen Damage*, PowerPlant Chemistry, 2010, 12(2), pp 122-127).

Acid phosphate corrosion (APC) relates to a plant using phosphate blends which have sodium-to-phosphate molar ratios below 2.6 and/or the use of congruent phosphate treatment using one or both of mono- or di- sodium phosphate. (Source: R.B. Dooley and A. Bursik, *Acid Phosphate Corrosion*, PowerPlant Chemistry, 2010, 12(6), pp 368-372).

Caustic gouging (CG) involves the concentration of NaOH used above the required control level within caustic treatment, or with the use of coordinated phosphate with high levels of free hydroxide, or the ingress of NaOH from improper regeneration of ion exchange resins or condenser leakage (fresh water cooling). (source: 14. R.B. Dooley and A. Bursik, *Caustic Gouging*, PowerPlant Chemistry, 2010, 12(3), pp 188-192).

The UDC mechanisms of hydrogen damage and caustic gouging have been well understood in fossil plants for over 40 years, and the acid phosphate mechanism since the early 1990s. Despite this, these mechanisms have become frequent problems worldwide in HRSGs. This may be because until recently the understanding of how the initiating deposition takes place in HRSG HP evaporator tubing has been less well understood than in fossil plants as well as the level of deposits necessary for these mechanisms to initiate by concentration within thick deposits. This has changed recently with work we've initially conducted: information from over 100 HRSGs worldwide has led to a new understanding on where to sample and how to analyze HRSG tubes for deposits and how to determine

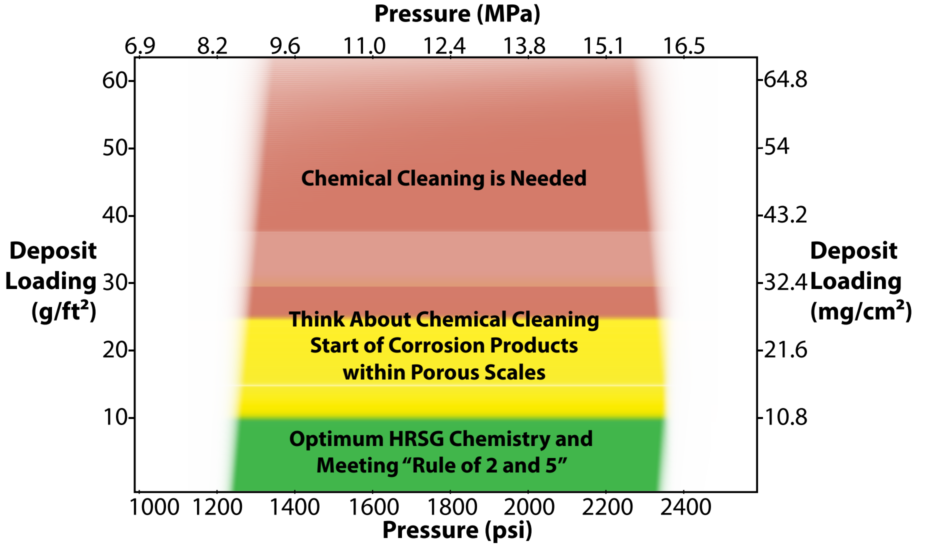


Figure 2: IAPWS Deposit Map for HRSG HP Evaporator tubes.

if the HRSG needs to be chemically cleaned. This will be published as an IAPWS Technical Guidance Document in September 2016 (see bibliography).

Deposition in HRSG HP Evaporators. Deposition and the UDC mechanisms can occur on both vertical and horizontal HRSG HP evaporator tubing. On vertical tubing the deposition usually concentrates on the internal surface (crown) of the tube facing the gas turbine (GT). It nearly always is heaviest on the leading HP evaporator tube in the circuit as these are the areas of maximum heat flux. Area of concentration can be the tube circuits adjacent to the side walls or to the gaps between modules due to gas by-passing. The UDC mechanisms usually occur in exactly the same areas. On horizontal tubing in vertical gas path HRSGs both deposition and the UDC mechanisms occur on the ID crown facing towards or away from the GT.

Examples of deposit loadings from over 100 HRSGs worldwide were analyzed and used to develop the new IAPWS Deposit Map shown in Figure 2. Plants included cover a very wide range of HRSGs from 17 HRSG manufacturers with HP drum pressures spanning the range 8.9 to 15.2 MPa (1300 to 2200 psi) and with deposits up to 136 mg/cm^2 (125 g/ft^2).

Some general comments reproduced from the IAPWS document can be made about the three colored cloud regions:

- The green cloud represents deposit levels from HRSG plants operating with optimum chemistries outlined in Part 1 of our News and Views series. The color of the internal surfaces under these optimum chemistry conditions are generally red / brown indicative of transported hematite from the lower pressure circuits. Importantly, in no cases was concentration identified or reaction products observed in the deposits near to the tube interface. This suggest that the risk for UDC mechanisms will be low.
- The yellow cloud generally represents the deposits in the HP evaporator in plants not using the optimum chemistry conditions such as by the use of reducing agents. The internal surfaces under these chemistry conditions are generally much darker and in most cases black.
- Towards the top of the yellow cloud and always in the red cloud there is evidence for concentration being identified or reaction products being observed in the deposits near to the tube interface. The internal tube surfaces are most often black indicative of transported magnetite.
- Clearly as HP evaporator deposits become thicker and exceed about 25 mg/cm^2 (20-25 g/ft^2) (top of the yellow band and into the red band) they become more porous and thus become more susceptible to concentration mechanisms and corrosion reactions at the base of the deposits next to the tube surface. These are the exact concentration processes that initiate UDC and should be avoided. Thus if HP deposit analyses indicate levels within the red cloud then the HRSG operator should consider chemical cleaning.

This new concept contained within the background of the Deposit Map for avoiding deposits which are thick enough to allow concentration provides the first step of avoiding UDC.

Continued on next page

1.1.4 STEAM TURBINE PHASE TRANSITION ZONE FAILURE/DAMAGE

Impurities in the steam from the superheater and reheater of plants may cause deposits and corrosion in steam turbines and thus the steam purity controls most corrosion processes and is vital to plant reliability. These problems can usually be avoided by following the guidance in the IAPWS Steam Purity Technical Guidance Document which needs to be compatible with the condensate, feedwater and boiler/ evaporator chemistries introduced in Part 1.

The four most important corrosion-related failure / damage mechanisms in the low pressure (LP) steam turbine are deposition, pitting, corrosion fatigue and stress corrosion cracking. The local steam environment determines whether these damage mechanisms occur on blade and disk surfaces. The phase transition zone (PTZ), where the expansion and cooling of the steam leads to condensation, is particularly important. A number of processes that take place in this zone, such as precipitation of chemical compounds from superheated steam, deposition, evaporation, and drying of liquid films on hot surfaces, lead to the formation of potentially corrosive surface deposits. Understanding the processes of transport, droplet nucleation, the formation of liquid films on blade surfaces, and concentration of impurities is vital to understanding how to avoid corrosion-related damage, and to improve unit efficiency/capacity.

The following two cycle chemistry operating regimes are identified as relevant to steam turbine corrosion. Of course, adequate materials properties (composition, structure, internal stresses, etc.) and design (temperature, stresses, crevices, etc.) also play essential roles.

- The dynamic environment during turbine operation. These are the local conditions formed by the condensation of steam as it expands through the PTZ of the turbine, and by the deposition of salts, oxides and other contaminants directly onto steam path surfaces.
- The environment produced during shutdown. These are the conditions that occur during unprotected shutdown when oxygenated moist / liquid films form on steam path surfaces as a result of hygroscopic effects. These films are directly caused by inadequate shutdown practices adopted by the plant operator. They can lead to pitting, which is most often the precursor to steam turbine corrosion mechanisms.

Thus, if adequate layup protection (dehumidified air (DHA)) is not provided, serious corrosion damage may occur even with the best operating chemistry, materials, design, and with only few major deposits.

Impurities can enter the steam by the following processes:

- Drum carryover of boiler / evaporator water
- Volatility in evaporating boiler / evaporator water
- Injection of feedwater into the superheater or reheater for attemperation

A complete description of the chemistry in the PTZ of the LP steam turbine includes the processes of moisture droplet nucleation, liquid film formation on turbine parts, deposition of oxides and impurities on surfaces, and how inadequate shutdown practices results in pitting. The major failure mechanisms of corrosion fatigue and stress corrosion cracking are initiated at pits so this sequential process is most important.

Steam Purity Limits. For plants with condensing turbines operating with superheated steam the following guidelines limits are suggested by IAPWS:

These limits are considered as the normal operating values during stable operation to avoid the steam turbine damage mechanisms and are consistent with longterm turbine reliability.

Steam Purity Startup Limits. Steam should not be sent to the turbine if the concentration of sodium exceeds 20 ppb (µg/kg). The immediate need at startup to ensure compliance with this limit requires a sodium monitor for steam. Steam also should not be sent

PARAMETER	UNIT	NORMAL / TARGET VALUES
Conductivity after cation exchange @ 25 °C	μS/cm	< 0.20
Sodium as Na	μg/kg	< 2
Silica as SiO_2	μg/kg	<10

Table 2. Steam purity for condensing turbines with superheated steam in fossil and combined cycle / HRSG plants.

to the turbine if the CACE (cation conductivity) exceeds 0.5 μS/cm. Allowance may be given to possible contributions from carbon dioxide and for sodium in units that only use tri-sodium phosphate in the boiler / evaporator water. The actual contribution of carbon dioxide must be measured and regularly verified for the specific plant. Degassed CACE can help to estimate the contribution of carbon dioxide.

Unit Shutdown Limits. In addition to operating with a set of normal and action levels it is also necessary to define a set of cycle chemistry conditions under which a unit must be shut down because of severe contamination. Shutdown conditions usually involve defining a steam CACE that indicates serious acidic contamination. Typically, a value of 1 μS/cm can be used under conditions that coincide with other upset conditions in the steam / water cycle. Carbon dioxide from air in-leakage or certain conditioning agents may warrant a less stringent CACE.

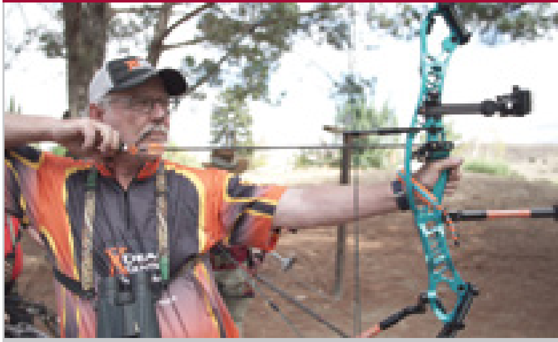
2.0 SUMMARY

Here we've provided a brief overview of the most important cycle chemistry influenced failure and damage mechanisms in fossil and combined cycle plants. The third article in this series will describe the assessment methodology we developed to identify proactively if any of these mechanisms will occur in a plant. It will illustrate how RCCS can identify how operating outside of optimum treatments and without adequate cycle chemistry control systems (monitoring, instrumentation, analysis, etc) will lead to failure / damage of the plant.

3.0 BIBLIOGRAPHY

There are a plethora of international guidelines and guidance available in many countries of the world for the reader: IAPWS (International), EPRI (US), VGB (Germany), JIS (Japan), Russian, Chinese, Manufacturers of major fossil and combined cycle / HRSG equipment (International), Chemical Supply Companies (International). Structural Integrity Associates uses the Technical Guidance Documents (TGD) of the International Association for the Properties of Water and Steam (IAPWS) in all the cycle chemistry related plant assessments and root cause analyses conducted. These are freely downloadable on the IAPWS website (www.IAPWS.org). These have been used as the reference materials throughout this document and full attribution is given to IAPWS.

IN THE NEWS



Many may not know but in his spare time Laney Bisbee, Structural Integrity's CEO, is an avid fly fisherman and competitive archer. Over the past 3 years he has been increasingly competing in local, state, national, and international archery tour-naments. This year, he has been selected by the National Field Archery Association (along with 6 other archers) to represent the US at the World Field Archery Championships being held in Wagga Wagga, New South Wales, Australia. Specifically, he will be representing the US in the Bowhunter Unlimited Class (Bowhunter Freestyle in the US).

INDUSTRY PROGRESS WITH SECOND LICENSE RENEWAL

By: TERRY HERRMANN
therrmann@structint.com

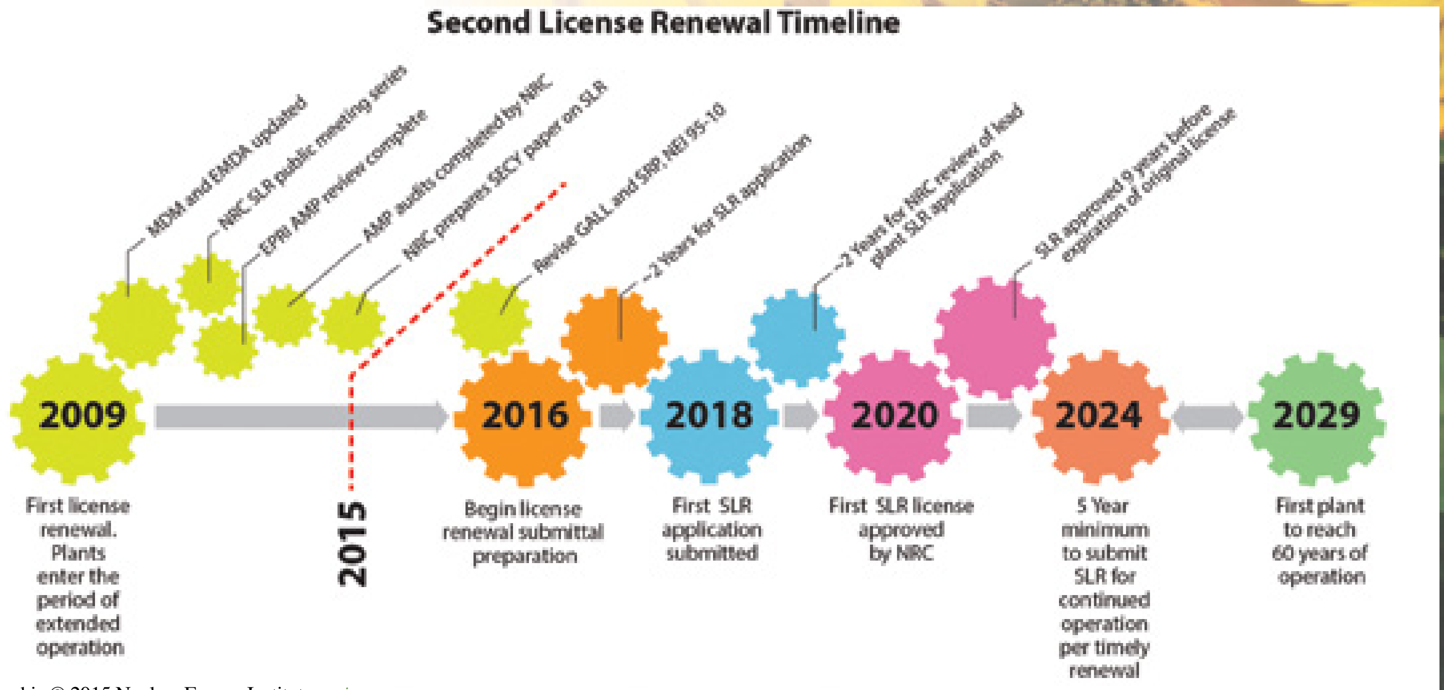
The US nuclear landscape has been undergoing some significant changes since News & Views last went to press. By 2040, half of the US nuclear plants will have been operating for 60 years, the end of the first Period of Extended Operation (PEO) granted under 10CFR50.54. However, a number of plants have recently announced they will be ceasing operations either before they reach the end of their original 40 year operating license or not long after they enter their PEO due to economic pressures. In another development, a desire to reduce greenhouse gas emissions from power plants is leading to changes that make it worthwhile for owners of nuclear generating plants to seek to operate their plants for an additional 20 years following the initial PEO.

Accordingly, the NRC and nuclear industry are preparing for the next round of Second License Renewal (SLR) applications with the first applications expected to be submitted in 2018. The two lead plants are Dominion's Surry station and Exelon's Peach Bottom station. Structural Integrity is currently providing technical support for both of these plants.

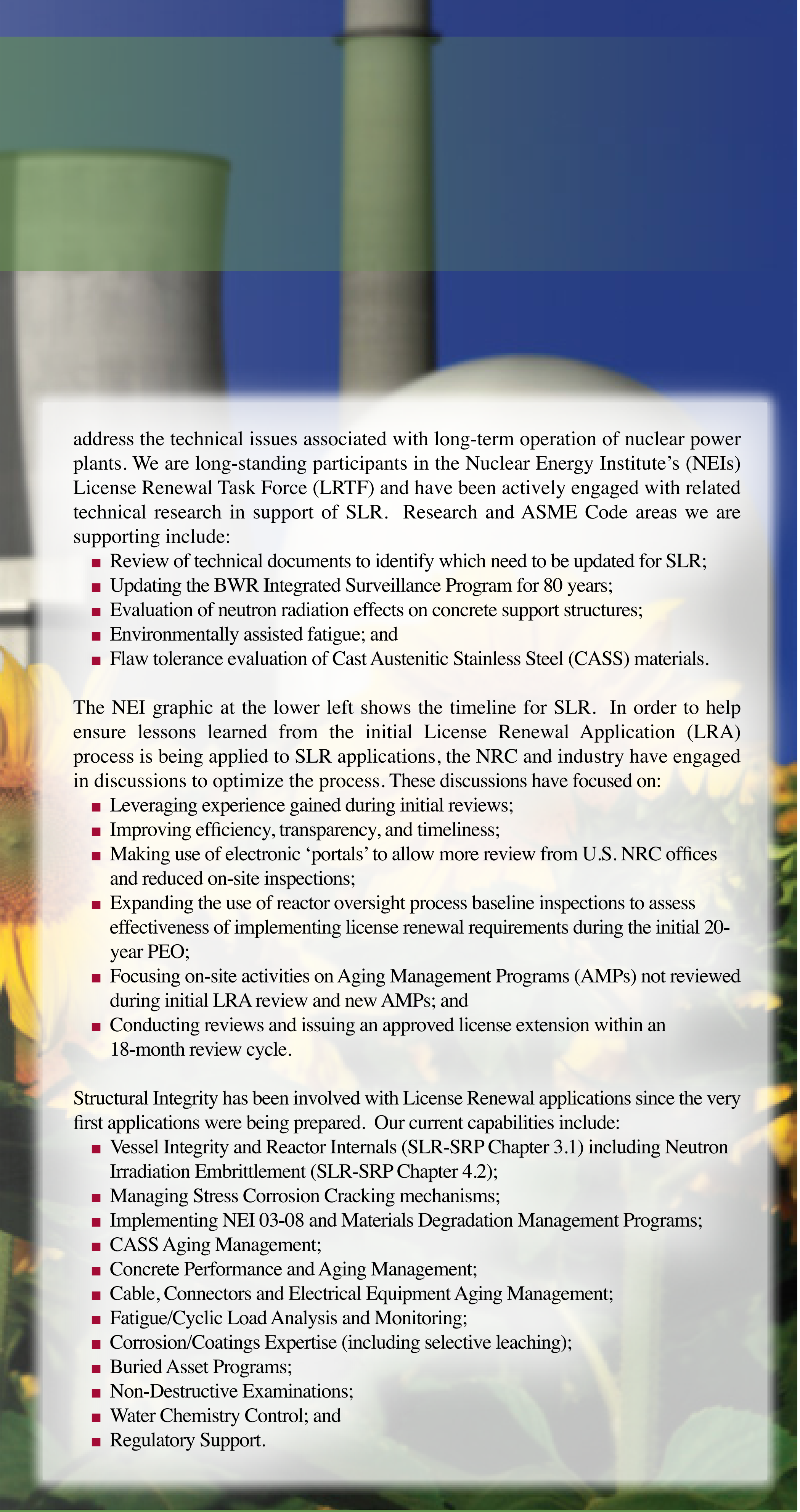
While the regulations for License Renewal is unchanged (10CFR54), the guidance being used for SLR applications is being revised with active involvement of both the NRC and industry. The industry and NRC have been participating in a number of public meetings to review and comment on draft reports of the Standard Review Plan (SRP-SLR, NUREG-2192) and Generic Aging Lessons Learned for Subsequent License Renewal (GALL-SLR, NUREG-2191).

The next step in this process is for the NRC staff to disposition comments received and technical bases for these documents. Following that, the documents will be reviewed by the NRC Office of General Counsel and the Advisory Committee for Reactor Safeguards (ACRS). Both documents are scheduled to be published in July 2017.

The Electric Power Research Institute (EPRI), through its Long Term Operations (LTO) program and US Department of Energy (DOE) through its Light Water Reactor Sustainability (LWRS) program have been funding ongoing research to



Graphic © 2015 Nuclear Energy Institute, nei.org



address the technical issues associated with long-term operation of nuclear power plants. We are long-standing participants in the Nuclear Energy Institute's (NEIs) License Renewal Task Force (LRTF) and have been actively engaged with related technical research in support of SLR. Research and ASME Code areas we are supporting include:

- Review of technical documents to identify which need to be updated for SLR;
- Updating the BWR Integrated Surveillance Program for 80 years;
- Evaluation of neutron radiation effects on concrete support structures;
- Environmentally assisted fatigue; and
- Flaw tolerance evaluation of Cast Austenitic Stainless Steel (CASS) materials.

The NEI graphic at the lower left shows the timeline for SLR. In order to help ensure lessons learned from the initial License Renewal Application (LRA) process is being applied to SLR applications, the NRC and industry have engaged in discussions to optimize the process. These discussions have focused on:

- Leveraging experience gained during initial reviews;
- Improving efficiency, transparency, and timeliness;
- Making use of electronic 'portals' to allow more review from U.S. NRC offices and reduced on-site inspections;
- Expanding the use of reactor oversight process baseline inspections to assess effectiveness of implementing license renewal requirements during the initial 20-year PEO;
- Focusing on-site activities on Aging Management Programs (AMPs) not reviewed during initial LRA review and new AMPs; and
- Conducting reviews and issuing an approved license extension within an 18-month review cycle.

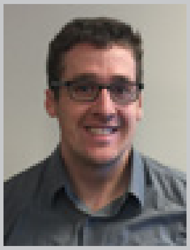
Structural Integrity has been involved with License Renewal applications since the very first applications were being prepared. Our current capabilities include:

- Vessel Integrity and Reactor Internals (SLR-SRP Chapter 3.1) including Neutron Irradiation Embrittlement (SLR-SRP Chapter 4.2);
- Managing Stress Corrosion Cracking mechanisms;
- Implementing NEI 03-08 and Materials Degradation Management Programs;
- CASS Aging Management;
- Concrete Performance and Aging Management;
- Cable, Connectors and Electrical Equipment Aging Management;
- Fatigue/Cyclic Load Analysis and Monitoring;
- Corrosion/Coatings Expertise (including selective leaching);
- Buried Asset Programs;
- Non-Destructive Examinations;
- Water Chemistry Control; and
- Regulatory Support.

IN THE NEWS

ASME
SETTING THE STANDARD

TIPPLE LENDS EXPERTISE TO ASME BPV VIII COMMITTEE



As experts in their chosen fields, the professionals at Structural Integrity frequently participate on committees to advance technical knowledge and safety in the energy industry.

In a recent appointment, Senior Engineer Chris Tipple was named a member of ASME's Resource Development Group for BPV VIII. His five-year term took effect in August 2016 and will expire in June 2021.

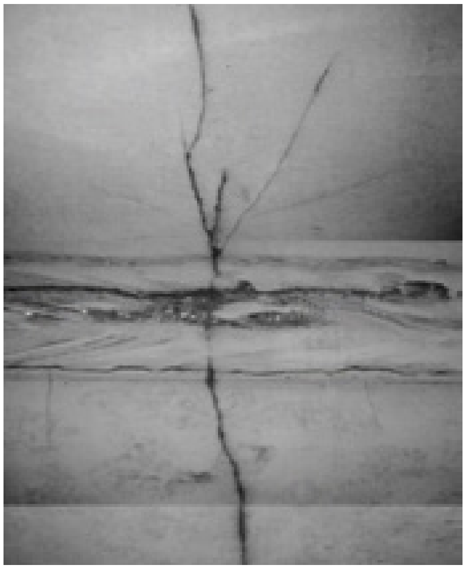
This committee is chartered with establishing, for publication in Section VIII of the Boiler and Pressure Vessel Code, rules relating to pressure integrity governing the construction of pressure vessels.

Structural Integrity fully supports our many employees who play an active role in the industries we serve, and we commend Chris on this ASME appointment.

STRUCTURAL INTEGRITY ASSOCIATES LEADS PROJECT TO TEST BWR CORE SHROUD BOAT SAMPLE

By: *DANIEL SOMMERVILLE, P.E.*
dsommerville@structint.com

Structural Integrity Associates, Inc. (SI) is nearing the end of a three year, successful effort funded by the Electric Power Research Institute (EPRI) to lead a diverse team of engineers and scientists from across the United States in performing metallurgical testing and evaluation of an irradiated material sample removed from an operating Boiling Water Reactor (BWR). Our team, composed of experts, from SI, BWXT NOG Technologies, Inc., Pacific Northwest National Laboratory and EPRI investigated the nature of off-axis cracking observed in the beltline region of the core shroud in a domestic BWR. It is a rare and expensive occurrence to remove and test in-vessel specimens. Consequently, selecting qualified vendors capable of performing work on highly irradiated materials, possessing appropriate knowledge of degradation mechanisms relevant to the BWR environmental conditions, and having the ability to interpret the significance of the data and relevance of the findings to the operation and management of the BWR fleet, is critical. Selection of the SI team as the most qualified team to perform this work is notable since numerous organizations from around the world, including original equipment manufacturers and scientific institutions, had submitted proposals for consideration.



Photograph illustrating atypical cracking observed in domestic BWR core shroud.

The experimental program was performed to investigate the likely cause of the off-axis cracking observed in the domestic BWR core shroud. The cracking was considered off-axis since it exhibited visual characteristics considered unusual for intergranular stress corrosion cracking (IGSCC) commonly observed in the BWR core shroud weld heat affected zones (HAZs). Specifically, the off-axis cracking exhibited the following unusual characteristics:

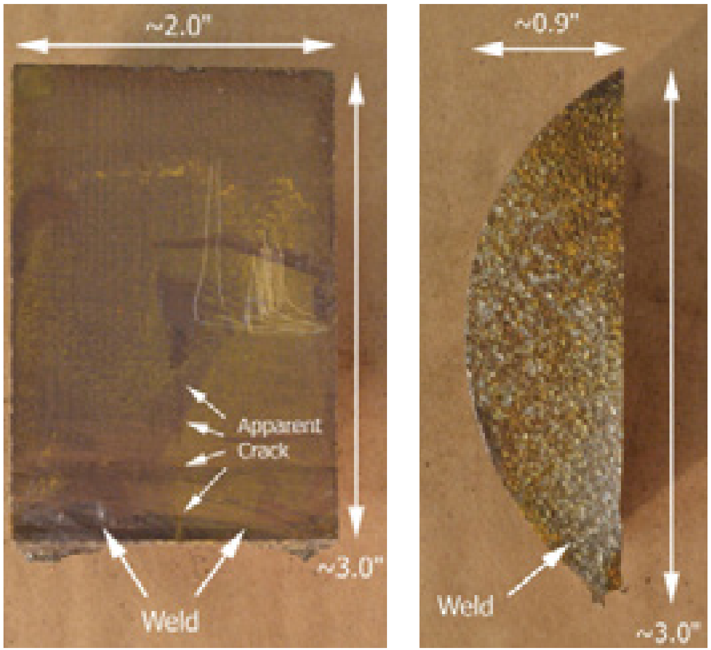
- Propagation transverse to the weld rather than parallel to the weld HAZ,
- Propagation into the non-sensitized base material generally considered not to be susceptible to IGSCC since this material would not have been weld sensitized, and
- Propagation through the weld material generally considered to be more resistant to IGSCC.

The fundamental question to answer was whether the cracking was attributable to irradiation-assisted stress corrosion cracking (IASCC) or whether it was sensitization related IGSCC. The significance of this question lies in the possible implications that IASCC initiation and growth into base material could have on the manner in which the industry manages aging of the core shroud assemblies.

To answer these and other questions, the SI team, with valuable contributions from EPRI and its individual consultants, initiated a multifaceted experimental program consisting of optical metallography, scanning electron microscopy (SEM), analytical transmission electron microscopy (ATEM), mechanical property measurement (tensile and fracture toughness testing), hardness testing, retrospective dosimetry measurements, and material composition confirmation using inductively coupled plasma mass spectrometry (ICP-MS). Specimens were machined at the BWXT facility in Virginia and tested both at BWXT and at the PNNL facility in Washington state.

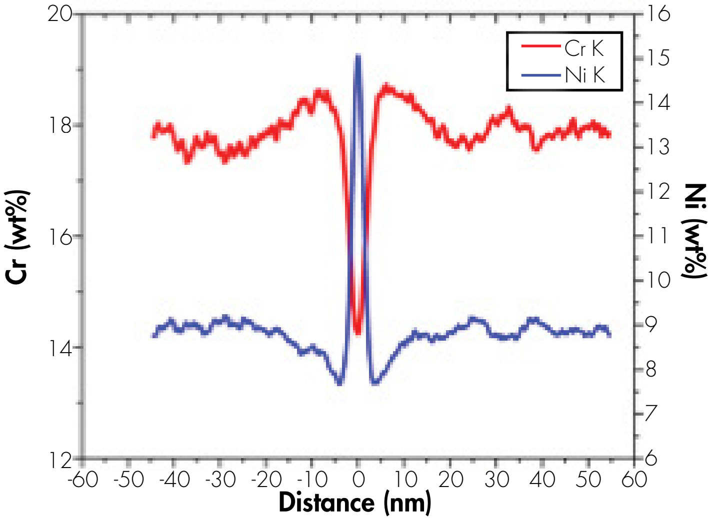
Before the experimental program could begin the irradiated material specimen had to be loaded into a cask and shipped to the BWXT facility. This step in the process possessed its own logistical complications requiring flexibility and collaboration among all project participants including, most notably, the utility. The success of this initial and vital activity was an early indication of the industry support for this project and commitment to success. Once we received the core shroud sample, our team could begin work in earnest.

Review of the body of data collected showed that while there was clear evidence of radiation damage to the material such as

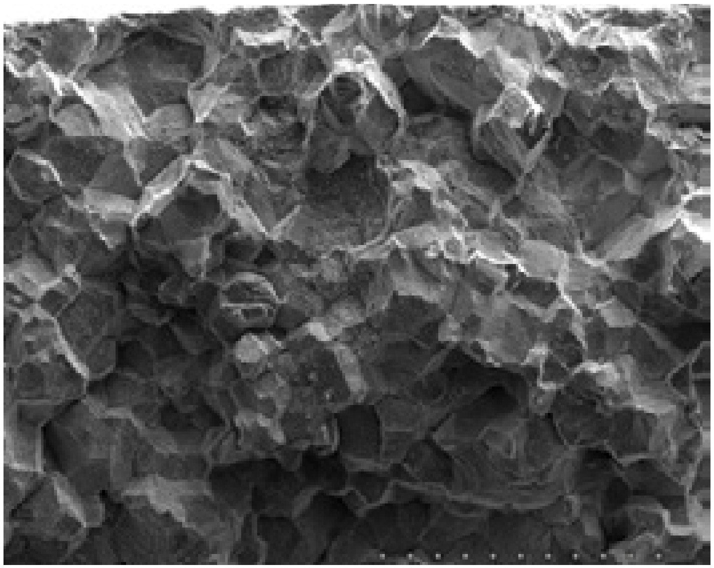


Photograph of core shroud boat sample.

radiation-induced segregation (RIS) of nickel and chromium along the grain boundaries and elevated through-thickness hardness resulting in radiation-induced susceptibility, there was also strong evidence of elevated surface hardness. This could have been the result of a surface mechanical treatment such as grinding that would also have caused the material to be susceptible to IGSCC initiation due to cold work. This observation, taken with the clear evidence of intergranular cracking as shown in the photomicrographs, suggested that the cracking was SCC and that the initiation mechanism could not conclusively be distinguished between cold work-induced IGSCC that had initiated earlier in operation or IASCC initiated later in operation. We considered it probable that the cracking initiated earlier in plant operation as a result of surface cold work, grew under the influence of locally high weld residual stress and propagated into the base material as the cumulative neutron fluence made the material microstructure susceptible to SCC as a result of radiation-induced segregation and hardening.

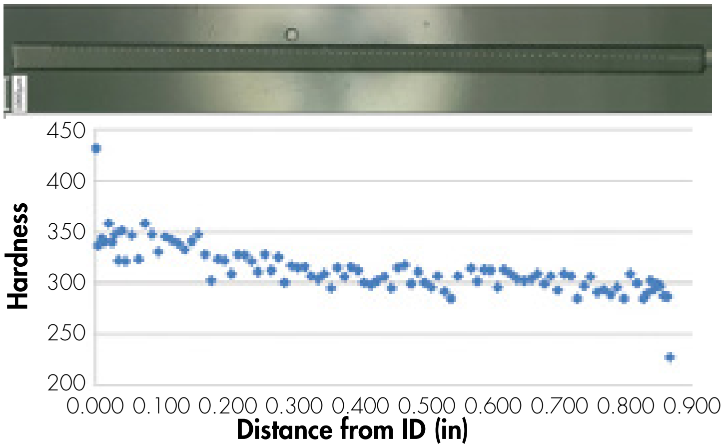


EDS compositional profiles across a high-angle grain boundary in the base metal, showing grain boundary enrichment of Ni and depletion of Cr. Segregation occurs within a narrow band within approximately 5 nm of the grain boundary.



SE-SEM image of base metal open crack surface (shroud ID surface is at top edge of image). Fracture features are consistent with intergranular corrosion. HAZ surface is similar in appearance.

The experimental results of this study, when combined with the results of related work on the topic, supported the conclusion that the existing core shroud aging management guidelines documented in BWRVIP-76, and augmented by the off-axis cracking inspection and evaluation guidelines, published by EPRI in 2016, provide an effective basis for BWR core shroud aging management.



Micrograph (top) and data plot (bottom) showing full-thickness microhardness traverse extending from the ID surface (at left) to the back side of the boat sample (at right).

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TRAINING CALENDAR

NOV
01

ASME Code Section III - Huntersville, NC

NOV
03

ASME Code Section XI - Huntersville, NC

NOV
08

Corrosion and Corrosion Control - Microbiologically-Influenced & Other Raw Water Corrosion - San Jose, CA

NOV
14

Corrosion and Corrosion Control in Light Water Reactors - November 14-18 San Jose, CA

NOV
15

Welding & Materials - Huntersville, NC

Flaw Evaluations – ASME Code Case N-513 - Denver, CO

NDE for Engineers and Managers - Huntersville, NC

DEC
06

Fuel Manufacturing Issues Affecting Performance - San Diego, CA

ASME Code Section VIII - High Pressure Vessel Design by Analysis - Huntersville, NC

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Session 4: Welding of Carbon and Low Alloy Steels *Tuesday, January 17, 2017 2:00 pm EST*

Session 5: Welding of Austenitic Stainless Steels and Nickel-based Alloys *Wednesday, February 8, 2017 2:00 pm EST*

Session 6: Welding of Castings and Dissimilar Metal Weldments *Thursday, March 2, 2017 2:00 pm EST*

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