Structural Integrity Associates, Inc.®

2017 | VOLUME 43

NEWS & VIEWS

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LATITUDE 32

INNOVATING THE NDE DATA ACQUISITION PROCESS

In this Issue

President's Corner

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As an independent, employee-owned company, we manage our business following a conservative and purposeful philosophy. To keep us aligned with this philosophy, our vision is simply stated – be a Sustainable Growth Company.

Sustainability means that we must meet the needs of the present employee-owners without compromising the ability of future generations to meet their own needs. We realize that how we manage the business today has long-term impacts on the future success of the business, its shareholders, employees, clients and stakeholders. Sustainability supports our continued long-term financial success through commitments to staffing the company with world-class consultants, proper corporate governance, promoting innovation, delivering value solutions, and building client trust.

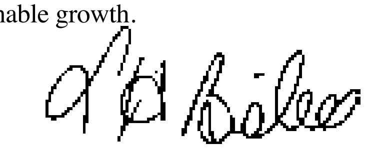
Many companies have fallen into the trap of managing for short-term results, whether driven by the desire of investors or by dressing a company up for a sale. We're fortunate to have long-term employee shareholders interested in playing the long game – just as our clients must make decisions that will pay off over years, if not decades. We purposely invest in innovative technologies and solutions instead of short term profits, and we prioritize client relationships over making an extra dollar from a particular project.

Growth at Structural Integrity is a sustained process of developing and diversifying to have significant and demonstrable impact on the markets we serve. Growth is the primary strategy to increase our competences in support of multi-disciplinary, integrated solutions and provide personal development opportunities for all employees. Growth must occur in multiple areas of the business if we are to be sustainable over many more decades.

We also seek growth in markets where we do not yet have a relevant impact. For those that have followed us, you have seen this goal realized in many of the technologies we develop and deploy for emergent industry issues and in our acquisitions. Specifically, you've seen acquisitions lead our expansion in oil and gas pipeline assessments, advanced NDE, nuclear fuels, structures, chemical engineering, and electrical consulting services in the past decade. As highlighted in this issue (on page 25), we have again expanded our technical competencies and served markets through the acquisition of Tobolski-Watkins, including TW Engineering and TRU Compliance.

TW Engineering is widely regarded as the foremost authority in specialty structural, earthquake and blast engineering with a core focus on providing technically defensible solutions for regulated markets. TWE develops creative and robust engineering solutions to resist extreme event loading in industries such as nuclear power, defense, life sciences, healthcare and government facilities. We have combined TW Engineering with SI's structures group and created a new business unit – Critical Structures and Facilities. In addition, through TRU Compliance, a TWE group, we offer special seismic, wind, and blast product certifications services for mechanical and electrical systems and components.

I hope you will take the opportunity to read the Critical Structures and TRU Compliance articles in this issue and become familiar with how they can support you. We are very excited to have these talented consultants join the other employee-owners of SI and contribute to our sustainable growth.



Attemperator Damage Prevention

A Case Study Using Online Monitoring

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Background

Attemperators (aka desuperheaters) are used in fossil and combined cycle plants to protect boiler/HRSG components and steam turbines from temperature transients that occur during startup or load changes. The attemperator sprays water droplets into the superheated steam to ensure that the downstream, mixed, steam temperature will not adversely affect downstream components. While there are a number of attemperator designs and configurations (Figure 1 shows a schematic of a typical arrangement), all of them are potentially vulnerable to damage, making attemperators one of the most problematic components – particularly in combined cycle plants. If the causes of damage are not identified (and addressed) early, then cracking and steam leaks can occur leading to costly repairs and replacements.

The frequent cycling and wide operating range of combined cycle plants impose particular demands on attemperator functionality. Spraywater demand to the attemperator can fluctuate greatly within a startup where heat input to the boiler and steam flow are changing rapidly. At part load operation spraywater may be required continuously to moderate steam temperatures because of high exhaust gas temperature from the combustion turbine. Spraywater may also be demanded when duct burners are fired. The cycling and thermal shocking of valves and attemperator components can lead to wear-out and leak-by, resulting in poor spraywater atomization and inadvertent ingress of water. This can be compounded by poor attemperator piping arrangements with insufficient upstream or downstream straight lengths to provide proper mixing and evaporation of the spraywater droplets. Poor control logic can also contribute to problems with hunting of valves, inappropriate timing of spraywater, or spraying with insufficient temperature head for evaporation. These conditions often result in pooling of spraywater on the bottom of the pipe or impingement of spraywater droplets on downstream elbows or bends, both of which cause large temperature differentials resulting in high thermal stresses and consequently thermal fatigue damage and/or warping and distortion of the piping. Figure 2 shows common causes and effects of malfunctioning attemperators.

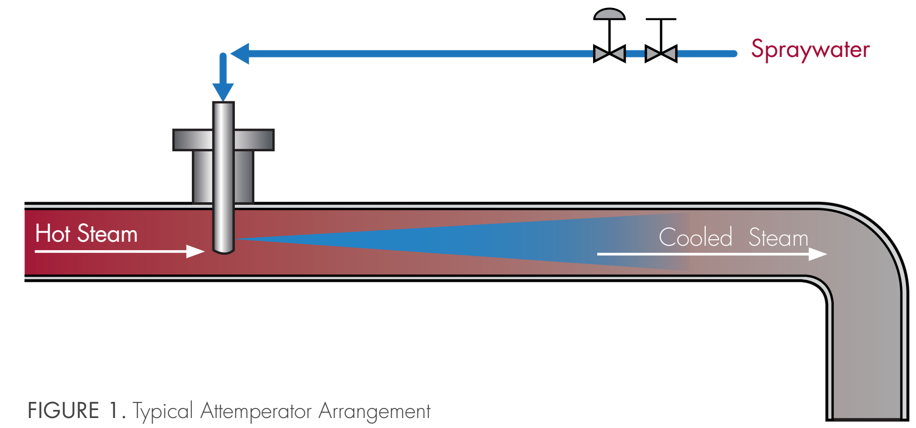

FIGURE 1. Typical Attemperator Arrangement

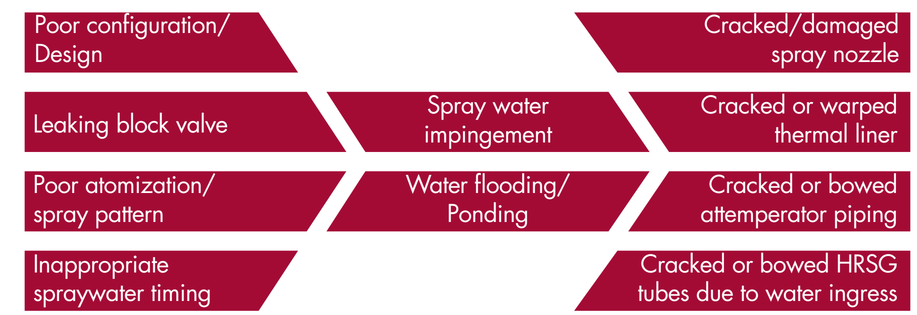

FIGURE 2. Possible causes and damaging effects of malfunctioning attemperators

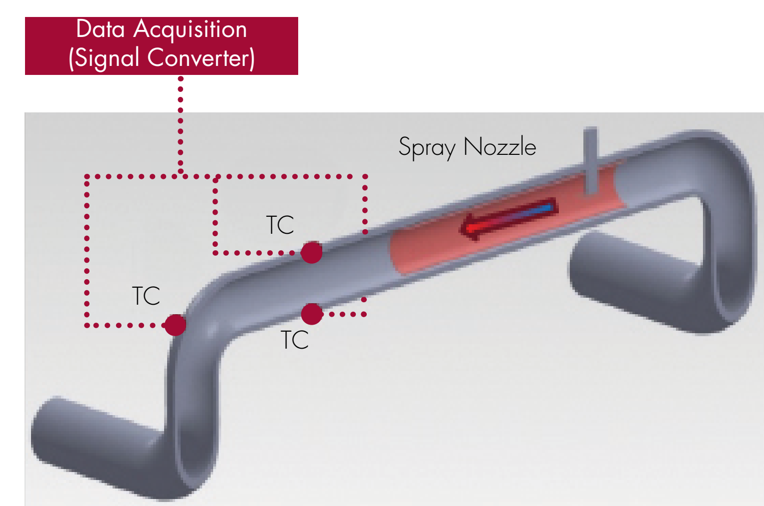

FIGURE 3. Typical thermocouple placement for Online Attemperator Damage Tracking System

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Attemperator Problems Lead to Forced Outages

In January of 2017 a power plant in the Northeast was experiencing recurring attemperator issues. The 620 MW Combined Cycle Electric Generating Facility consists of two combustion turbines, two heat recovery steam generators, and one steam turbine.

Upon inspection, the High Pressure final stage attemperators had cracked at the weld from the attemperator nozzle to steam piping and some of these cracks migrated into the bore of the piping. The liners were showing signs of cracking at the locations where they attach to the piping. Additionally, the spray water block valves showed signs of leakage. These and other attemperator issues forced the plant to shut down operations several times over the later part of 2016 and first part of 2017. While plans were made to repair the damage and address the design issue, the plant personnel contemplated what else could go wrong with the attemperator and became determined to take a proactive approach to maintaining the health of the system. Being well aware of the issues described above, they desired a system that could monitor for damage downstream of the attemperator in case of leaking, inappropriate control logic, etc.

The Solution

Because much of the damage to attemperator systems results from spraywater pooling or impingement it is effective to install thermocouples on the top and bottom (if the piping is nominally horizontal) of the piping downstream of the attemperator, and on the extrados of the elbow downstream of the attemperator. Such thermocouples installed on the OD of the piping have proven effective to detect leak-by, inappropriately timed spraywater, or damaged attemperator spray heads. To aid in detection of events and the magnitude of damage caused, SI has developed a real-time Attemperator Damage Tracking Application which processes the data from the thermocouples to determine the severity of events and incorporates a fatigue cycle counting algorithm to track the cumulative damage.

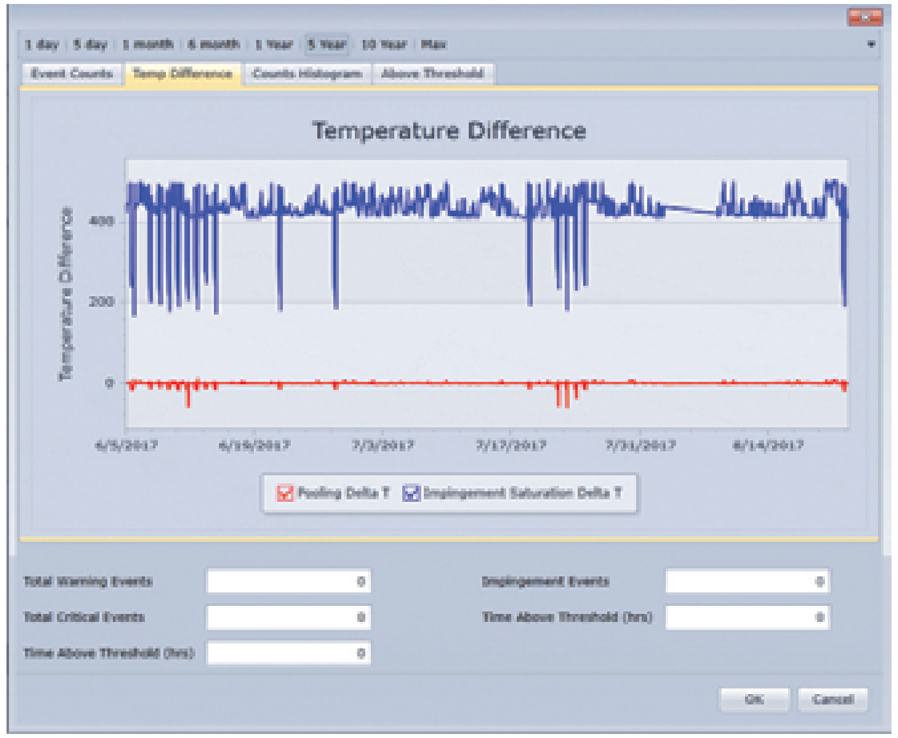


FIGURE 4. Example of an attemperator damage tracking app trending chart for temperature differentials

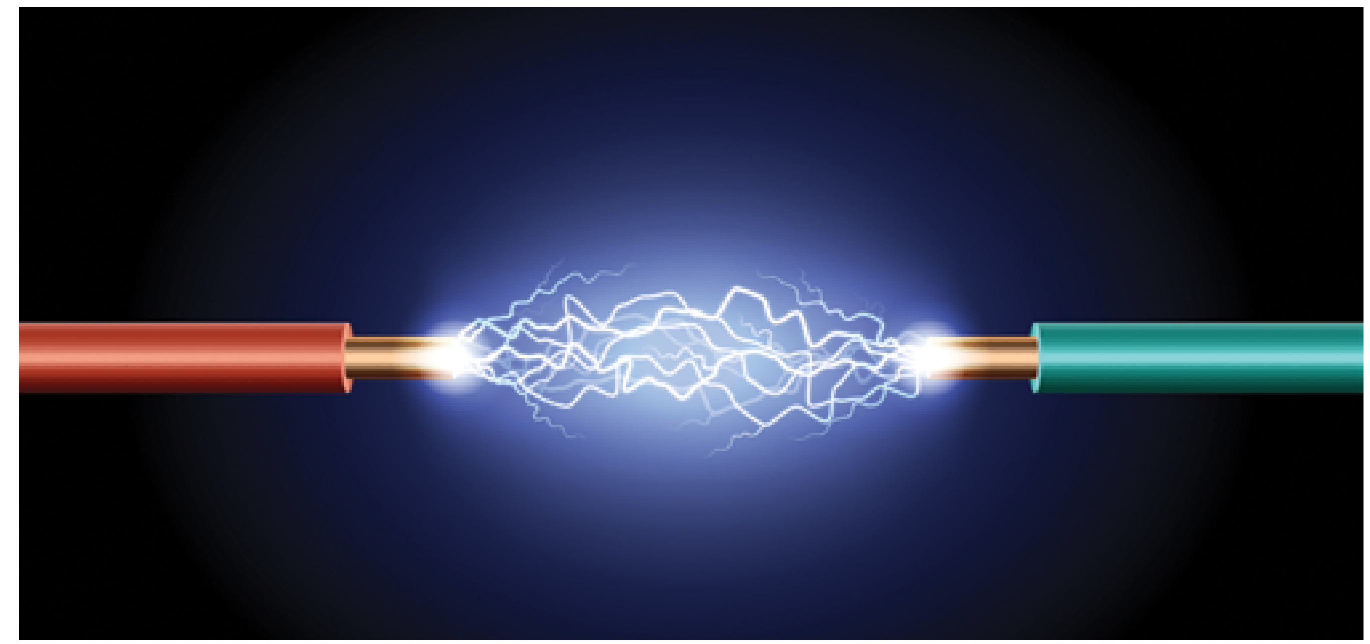
In the combined cycle plant described above, thermocouples were installed at three locations as shown schematically in Figure 3. This allows for detection of water pooling and impingement events. The thermocouples were mounted on the outside of the pipe and the signal is routed through a signal converter into the plant's data historian. From there, the Attemperator Damage Tracking App accesses the data remotely through the historian's web API. This setup allows for minimal installation effort and investment for plant operators.

The plant users access the App online through SI's web-based PlantTrack software to view data trends. Figure 4 is an example of one of the App screens, showing temperature differentials measured by the installed thermocouples. Based on the configured settings, the App filters these differentials and translates them into different event categories (e.g. critical vs. warning), which can then be analyzed in conjunction with other plant data to determine the cause and define mitigating actions. The software can also be configured to provide email alerts when certain events occur, or based on trends in damage accumulation. This allows early detection of potentially damaging events so that appropriate mitigations (maintenance, logic updates, etc.) can be performed before costly repairs are required.

A major advantage of PlantTrack's Online Attemperator Damage Tracking App is that it can detect temperature excursions regardless of the cause. This is helpful since the causes can be multifold, as described above. The alternative approach of monitoring specific causes (e.g. block valve settings), would oftentimes reveal only part of the picture and could lead to undetected damaging events.

The attemperator tracking solution is one of multiple Online Damage Tracking Apps SI has developed to help plant operators track critical components conditions. The Apps have been integrated into SI's PlantTrack software.

Relay Maintenance and Replacement Optimization



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Background

Relays play an important role in protection and control of electrical equipment in nuclear power plants. Thousands of relays perform various protection and control functions in each reactor unit. Plants normally replace relays "like for like," especially in safety related applications due to the high cost of modifications. Relay life-limit determination is often based on time in service, which has been conservatively developed and determined from the most limiting and severe environmental service applications. Based on industry testing, relay life is frequently significantly longer than currently used bases would predict.

Opportunity for Savings

Structural Integrity has supported several industry projects that provided key insights on relay performance, failure mechanisms and ultimate service life limits. For non-EQ (Environmental Qualification) relays, replacement intervals can be optimized based on actual service conditions and applications such as in-cabinet, in-room, and component specific parameters. Various models can also have differing service lives as some models are more tolerant than others.

Energized versus non-energized applications also make a difference in relay aging rates as they significantly impact relay internal operating temperatures. Organic components within the relay, particularly the relay coil insulation material, are the most limiting sub-component parts for normally energized relays. The heat rise associated with energizing the coil provides a natural aging stressor within the relay. This coil heat can also affect other relay subcomponents such as the bobbin, or armatures, or promote internal gassing that can impact the contacts.

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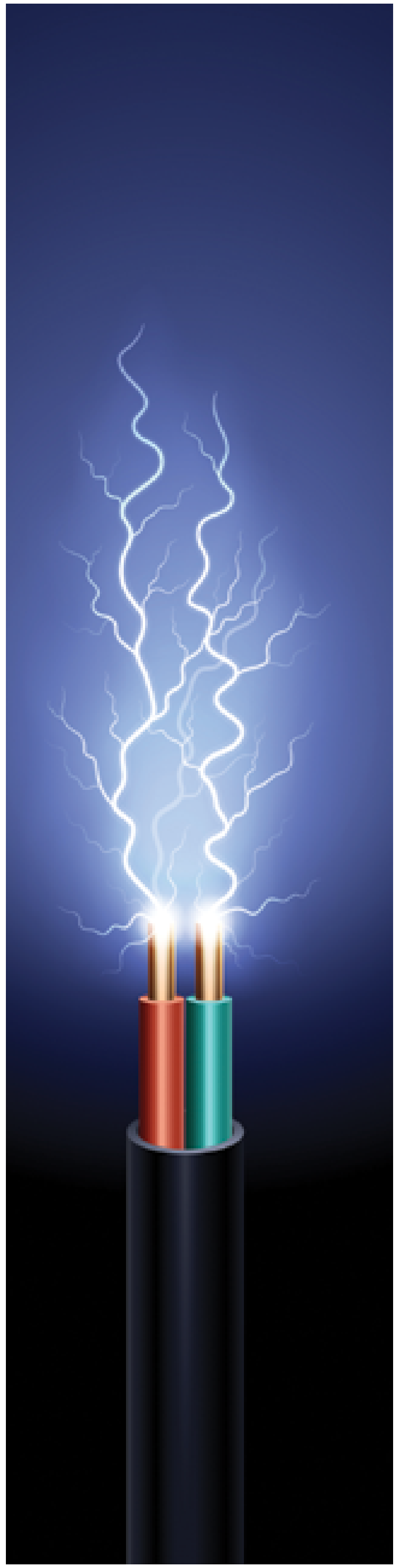


Temperature effects can be magnified when relays are placed in cabinets with nearby heat sources or clustered together in a single enclosure. Through application of Arrhenius methodologies, temperature correction factors can be developed and applied for a variety of applications to estimate relay life.

For timing relays, set point drift can be particularly challenging. Set point drift is also aggravated by high thermal aging stresses. On the other hand, lower thermal aging conditions can help maintain set point with lower levels of drift. For lower temperature applications, less frequent calibrations may be justified. For higher temperature applications, such as in warmer cabinets or with relay clusters, more frequent calibration should be considered.

The Agastat is a Tyco/TE Connectivity relay design

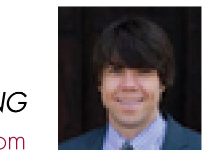
"Structural Integrity has supported several industry projects that provided key insights on relay performance, failure mechanisms and ultimate service life limits."

Due to the sheer number of relays in a plant, substantial savings can result from extending relay service life, or from longer calibration intervals or both. Specifically, savings exist in:

- Lower replacement part costs from extending relay replacement intervals
- Lower labor costs associated with less frequent relay replacements and calibration
- Reduced early failure risks associated with infant mortality that can occur with more frequent relay replacement. (New relays are more likely to experience early failures from manufacturing defects, mishandling, or installation issues.)
- Improved availability for relay applications where aging insights optimize replacement frequency.

Integrating the application specifics and relay type/model information results in a graded approach to relay calibration and replacement. The outputs from grading the relays can support an overall optimization pilot based upon model-specific performance, application environment (particularly temperature), and energized state of the relay (normally energized or normally de-energized). Pilot application across a variety of relays at a plant can serve to validate savings from a larger plant wide implementation effort. With thousands of plant relays, the integrated savings on labor and parts can be substantial and provide a good return on investment.

Perforation, Scabbing, and Reinforcement Optimization in an Aircraft Impact Analysis (AIA)



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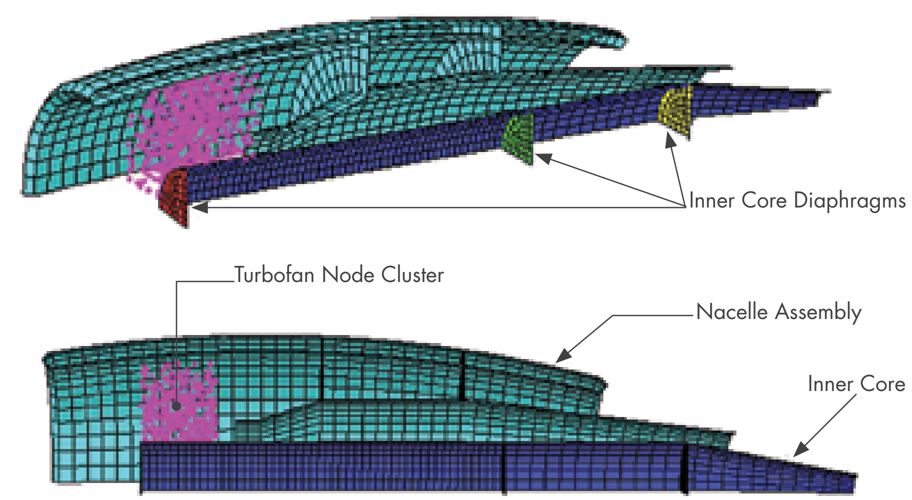

FIGURE 1. Engine Quarter-Model

Background

A 2016 project utilized a variety of Structural Integrity competencies to analyze a beyond design basis threat at an overseas nuclear power plant. The client was assessing a plant design and approached Structural Integrity to investigate local perforation and scabbing of a reinforced concrete wall due to hard missile impact. Perforation occurs when a missile fully penetrates and passes through a target while scabbing occurs when material is ejected from the back face of a target, potentially striking personnel and equipment inside the facility. The client also sought to reduce the volume of wall reinforcement, a potentially large cost savings, while still meeting the facility's strict design criteria. The project is best described in four stages and took advantage of our AIA experience, finite element (FE) modeling expertise, and proprietary concrete constitutive model ANACAP. The four stages of the evaluation are addressed as follows:

Developing the Hard Missile

The impacting missile was an airplane engine traveling at high velocity. A quarter-model of the engine (Figure 1) was developed through a three-step benchmarking process. First, the model's

Continued on next page

inner core was developed through an iterative process by benchmarking the core's post-impact residual velocity to Nuclear Energy Institute (NEI) available estimates. The inner core model was "launched" at concrete walls with various thicknesses, concrete strengths, and with various initial velocities to ensure that the inner cores' behavior matched predicted estimates within empirically tested limits (Figure 2). Models of the nacelle assembly and turbofan were developed in the second step using a similar benchmarking process. Finally, the Riera methodology [1] was used to compare the FE model's behavior to analytical estimates (Figure 3).

Developing a Scabbing Metric

A metric was needed to determine if concrete scabbing would occur during impact and, if so, its extent. NEI equations were used to determine at what velocity scabbing is expected to occur when a cylindrical missile (such as the inner core) is "launched" at various concrete walls. These velocities were used as inputs in FE models of the inner core to develop a metric that predicts when concrete scabbing is expected to occur.

This metric was verified by developing an FE model, which recreated a 1989 experiment performed as part of AIA qualification by the Central Research Institute of Electric Power Industry [2]. The experiment utilized scaled tests of hard missiles impacting reinforced concrete slabs and produced data relating to the slabs' structural resistance to missile perforation. The experiment also documented the extent of scabbing on the walls' non-impacted face. Structural Integrity's scabbing metric accurately predicted the extent of scabbing seen in the experimental results.

Assessing the Design Wall

Having developed a FE representation of the impacting engine and a metric to determine the extent of concrete scabbing, the benchmarked engine was "launched" at the design wall. The cover concrete on the non-impacted face was monitored for

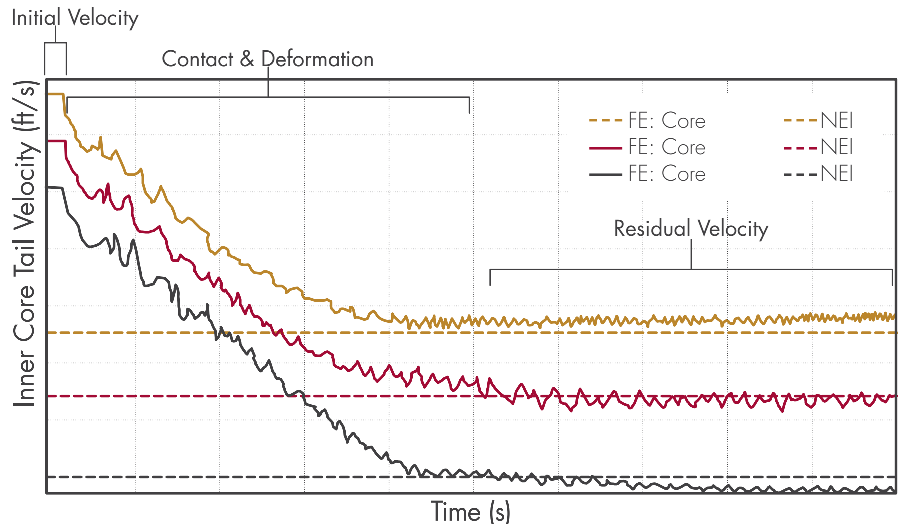

FIGURE 2. Perforation Benchmarking

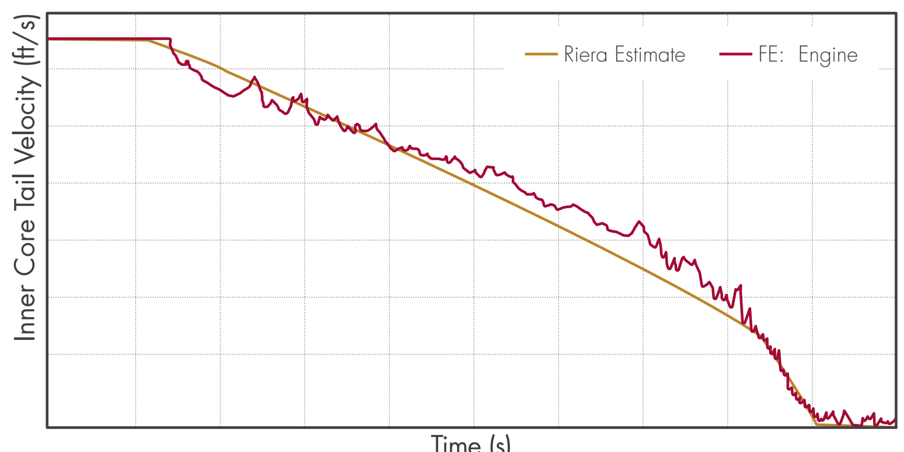

FIGURE 3. Riera Methodology Comparison

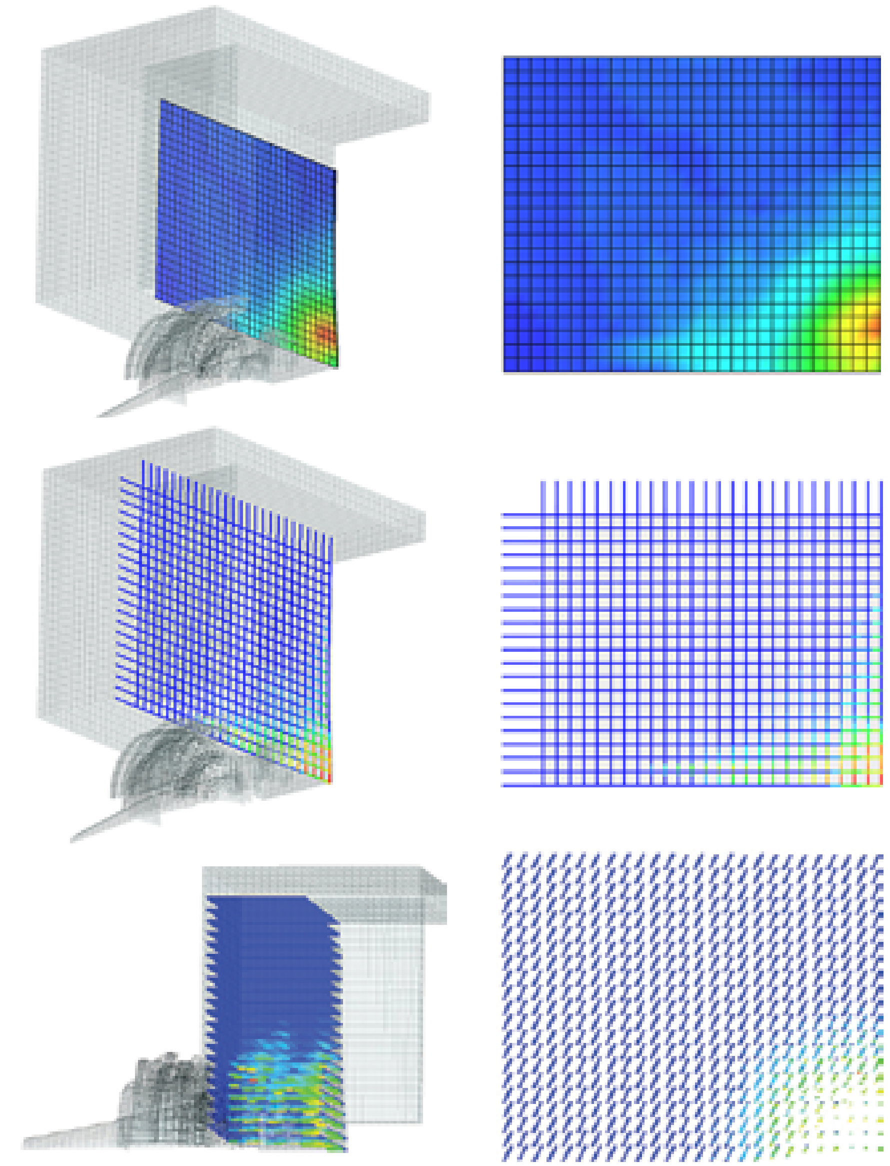

FIGURE 4. TOP Scabbing Metric
MIDDLE Longitudinal Reinforcement Plastic Strain
BOTTOM Transverse Reinforcement Plastic Strain

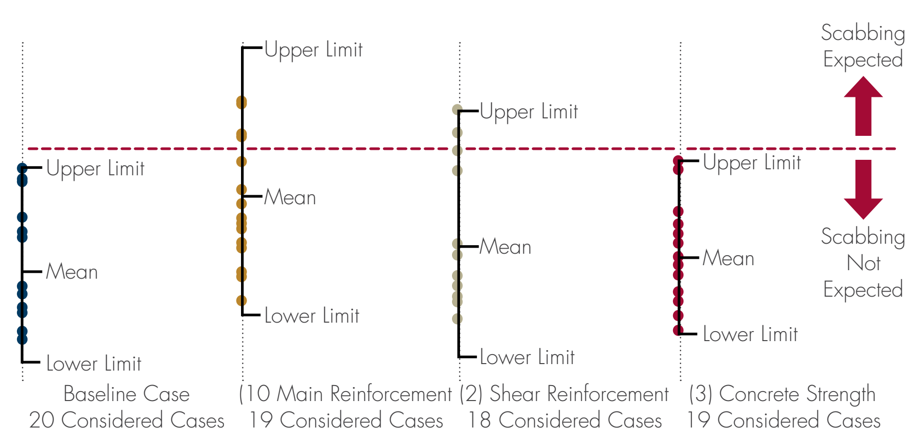

FIGURE 5. Optimization Study Results

scabbing. Plastic strains in the embedded reinforcement were also monitored (Figure 4). The analysis showed that the scabbing metric was not exceeded under the design conditions, and as such, there was good confidence that scabbing was not expected to occur.

Optimization Study

Since scabbing was not expected to occur in the design wall, an optimization study was performed to determine if alternative cost-saving configurations would also satisfy the design criteria. Three cost-saving configurations were investigated: (a) a reduction in main/longitudinal reinforcement, (b) a reduction in shear/transverse reinforcement, and (c) a reduction in concrete design strength. A parametric study was undertaken to determine how the three configurations would respond to the engine impact under slightly perturbed design inputs. The study indicated that a reduction in the walls' reinforcement or concrete strength would provide satisfactory behavior under best estimate (i.e., mean) conditions. An assessment utilizing higher confidence bands, typical of design basis assessments, showed that reducing the wall reinforcement may result in scabbing (Figure 5).

Conclusion

Structural Integrity utilized its AIA experience, finite element (FE) modeling expertise, and ANACAP concrete constitutive model to perform an optimization study that revealed that its client could meet nuclear facilities strict design criteria while reducing construction costs.

References

[1] ERIN Engineering & Research, Inc., "Methodology for Performing Aircraft Impact Assessments for New Plant Designs," NEI 07-13.

[2] Ito, C., Ohnuma, H., Shirai, K., et al., "Local Rupture of Reinforced Concrete Slab Due to Collision of Hard Missile," Paper presented at the 10th International Conference on Structural Mechanics in Reactor Technology, Anaheim, CA, USA, August 18, 1989.

Natural Gas Pipeline Safety Regulatory Compliance Workshop

Our Course Syllabus Includes

- An Overview of the Current Pipeline Safety Regulatory Environment, including the 2011 and 2016 Congressional Pipeline Safety Reauthorizations
- Part 191 Reporting Requirements and In-Depth Part 192 Overview
- Covered Pipelines, Definitions and Documents Incorporated by Reference
- Material Selection and Design of Pipe and Pipeline Components
- Welding of Steel, Fusion of Plastic, and Qualification of Procedures and Personnel
- Construction, Pressure Test and Records Requirements to Establish a Valid MAOP
- MAOP Record Retention Requirements
- Corrosion Control Requirements
- Operations Requirements
- Maintenance Requirements
- Transmission Integrity Management Program
- Distribution Integrity Management Program
- Overview of the Safety of Gas Transmission and Gathering Pipelines Mega-Rule and Anticipated Changes from the Extensive Proposed Rulemaking. Includes update on developments since the Notice of Proposed Rule-Making (NPRM) was issued

Meet Our Expert

Bruce Paskett is a licensed professional engineer with over 34 years of experience in the natural gas utility industry. He has been responsible for management of field personnel, corporate pipeline safety compliance, engineering operations, and major construction projects.

Bruce has extensive experience in developing realistic Gas Policies and Procedures that ensure compliance with relevant state and federal regulations. He has also worked with state and federal pipeline regulators to develop new pipeline safety regulations that are practical for the industry through his work with the American Gas Association.

Workshop Details

Join us for a 4-day training workshop that will provide a comprehensive and interactive overview of the Natural Gas Pipeline Safety Regulations, 49 CFR, Parts 191 and 192.

Presenter
Bruce Paskett, Structural Integrity's Chief Regulatory Engineer

When
October 23-26, 2017

Where
Charlotte, N.C.

Who Should Attend?

- Operations Managers
- Engineers
- Regulatory/Compliance Managers
- Maintenance and Inspection Managers
- TIMP and DIMP Managers
- Project Managers
- Field Supervisors
- Field Personnel

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In-Line Inspection

An Improvement Over Pressure Testing for Pipeline Integrity Management

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Structural Integrity recently performed probabilistic fracture mechanics (PFM) analysis of a gas transmission pipeline for a major U.S. operator. The analysis yielded interesting insights in several areas:

Pressure Testing versus In-Line Inspection
Pressure testing has long been considered the gold standard for assuring pipeline integrity. By testing at a factor (e.g., 1.25x or 1.5x) above the Maximum Allowable Operating Pressure (MAOP), any size critical flaws in the line would fail at this pressure level and are thus removed prior to future service. Subcritical flaws that remain after the test will be smaller than the critical flaw sizes during operation, and thus can be assumed to have some margin for growth before they become critical in service. Flaw growth rates can be calculated based on operational and environmental factors to establish a reassessment interval for future testing or inspections.

In-Line Inspection (ILI) technology has improved significantly in the areas of Probability Of Detection (POD) and flaw sizing accuracy, such that a greater level of safety may now be achieved through ILI. With accurate ILI and an associated repair criterion (i.e., repair all flaws greater than a specified size), smaller flaws and a greater numbers of flaws will be identified and repaired. This is particularly important when aggressive crack growth mechanisms are present, such as Stress Corrosion Cracking (SCC).

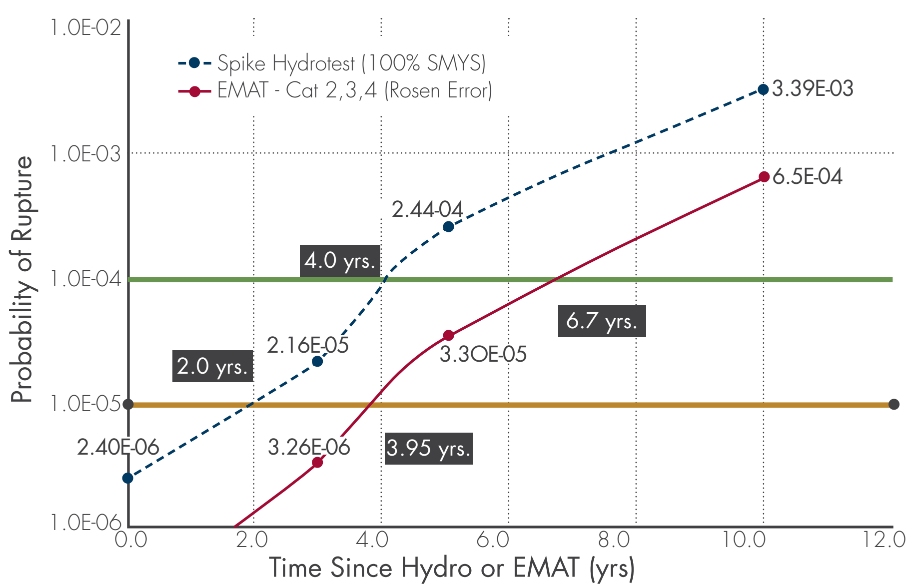

FIGURE 1. Rupture Probabilites @ MAOP

This point is illustrated in Figure 1 above, which presents the results of a probabilistic analysis of about 100 miles of gas transmission piping that had experienced an SCC failure and was subjected to a 100% ILI using advanced EMAT UT technology. The plots compare probability of failure versus time following the ILI or following a spike Hydrotest at a stress level equal to 100% of specified Minimum Yield Strength (SMYS).

While the results are acceptable with both techniques, they show that EMAT ILI outperforms Hydrotest – i.e. the EMAT ILI probability of failure (red curve) is consistently about an order of magnitude lower than the Hydrotest probability (dashed curve). This is a significant finding, as Hydrotesting can cost significantly more than ILI. In many cases, Hydrotesting is not a viable alternative since the pipeline is not looped or back-fed and therefore may not be taken out of service. A cautionary note, however, is that this result is highly dependent on the quality of the ILI technique. The above PFM analysis incorporated vendor-specified sizing error margins and PODs, which were validated via in-ditch and destructive measurements on a substantial number of detected features.

Reassessment Intervals
The PFM analysis can also provide guidance in establishing reassessment intervals. In theory, one just specifies an acceptable probability of failure (e.g., the horizontal green or yellow lines in Figure 1), and selects the intersection of that line with the applicable curve. For example, using the green line (10^{-4} failure probability), a 4-year reassessment interval is predicted for Hydro-test versus 6.7 years for EMAT ILI. Of course, acceptable failure probability is not obvious or easy to establish, so a perhaps more appropriate use of such PFM results is to evaluate existing reassessment guidance and make comparisons. For the subject pipeline, the operator's internal SCC management plan specifies a 3-year Hydrotest interval when a failure has occurred. Referring to Figure 1, that interval corresponds to a rupture probability between the 10^{-4} and 10^{-5} lines. An equivalent integrity level could be achieved by instead performing EMAT ILI on a 5-year interval.

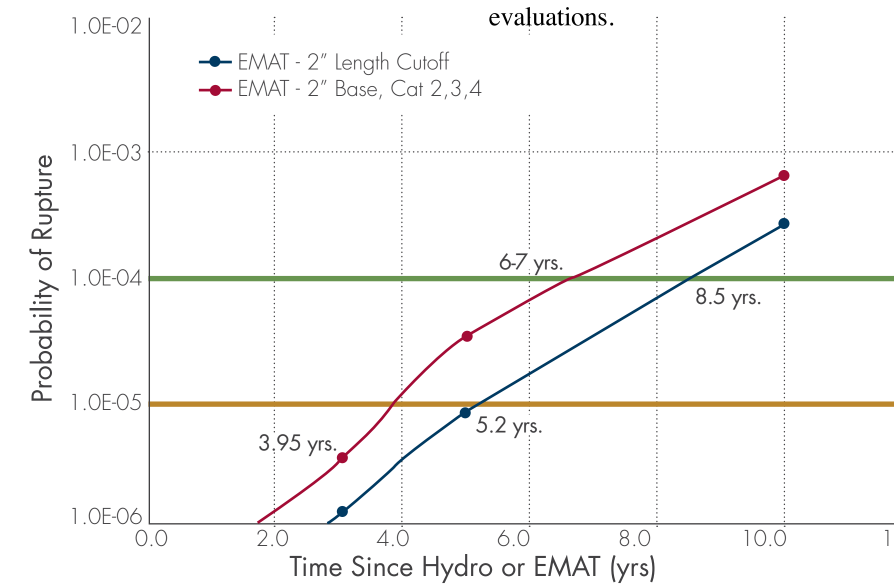

FIGURE 2. Rupture Probabilites @ MAOP ILI Repair Criteria Sensivity

Evaluating Tradeoffs
Finally, the PFM analysis can be used to evaluate tradeoffs among specific provisions of an integrity management plan. For example, the Figure 1 ILI result was based on an ILI repair criterion that requires all detected flaws greater than AMSE B31.8S Category 2 (flaws that would fail at 125% of MAOP) to be repaired. In Figure 2, this criterion was enhanced to specify repair of >Category 2 flaws plus any detected flaws with lengths greater than 2 inches, regardless of depth. The results show that this enhanced repair criterion adds about 1 to 2 years to the 10^{-5} and 10^{-4} reassessment intervals. Thus, an operator can use these results to compare the economics of enhanced repair criteria versus extended reassessment intervals, while maintaining the same level of pipeline integrity. PFM evaluations such as this could be used to perform many types of integrity management cost-benefit evaluations.

Delivering the Nuclear Promise:

Industry experience to date suggests that 75 percent of safety-related SSCs can be categorized as RISC-3, low safety-significant (LSS). This is important because (a) it provides a focus on safety significance and (b) RISC-3 SSCs are exempted from "special treatment" requirements.

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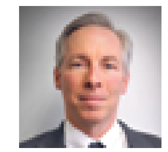
Delivering the Nuclear Promise:

10 CFR 50.69 Alternative Treatments for Low Safety-Significant Components



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As all of us who work with nuclear energy know the US nuclear industry is engaged in a multi-year effort to generate power more efficiently, economically and safely. A key goal includes a significant reduction in operating expenses. This initiative is termed "Delivering the Nuclear Promise" (DNP) and is supported by nuclear utilities, vendors such as Structural Integrity, the Nuclear Energy Institute (NEI), Institute of Nuclear Power Operations (INPO), and the Electric Power Research Institute (EPRI).

10CFR50.69' Risk Informed Engineering Programs (RIEP) is a regulation that enhances safety and provides the potential for large cost savings. This regulation allows plant owners to place systems, structures and components (SSCs) into one of the four risk-informed safety class (RISC) categories as indicated in the graphic to the right.

Industry experience to date suggests that 75 percent of safety-related SSCs can be categorized as RISC-3, low safety-significant (LSS), based on low risk. This is important because (a) it provides a focus on safety significance and (b) RISC-3 SSCs are exempted from "special treatment" requirements imposed by 10CFR50 Appendix B and other regulatory requirements (shown in the boxes at the bottom of page).

Savings from implementing Alternative Treatments

Since safety-related SSCs remain safety-related and retain their safety functions, what are "alternative treatments" and how do they generate cost savings? The difference is the level of rigor plant owners need to apply when demonstrating safety functions will be met.

Two DNP efficiency bulletins have been issued by NEI for the 50.69 initiative:

- EB 17-09 – Industry Coordinated Licensing of 10 CFR 50.69
- EB 17-16 – Industry Coordination of Categorization and Alternative Treatments for 10 CFR 50.69 Implementation Plans

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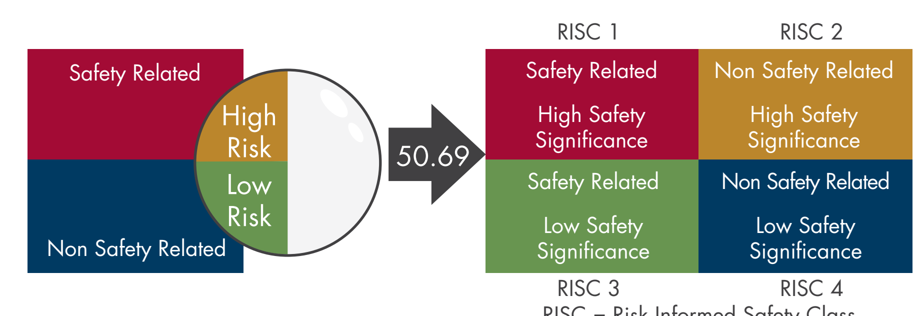

Categorization of plant SSCs per 10 CFR 50.69

Local Leak Rate Testing [10 CFR 50 Appendix J]	Quality Requirements [10 CFR 50 Appendix B]	In-service Inspection [10 CFR 50.55a(g)]	ASME XI Repair & Replacements, Applicable Portion, with Limitations[10 CFR 50.55a(g)]
Mainenance Rule [10 CFR 50.65]	In-Service Testing [10 CFR 50.55a(f)]	Environmental Qualification [10 CFR 50.49]	Event Reporting [10 CFR 50.55(e)]
Seismic Qualification [Portions of Appendix A to 10 CFR Part 100]	Deficiency Reporting [10 CFR Part 21]	Applicable Portions of IEEE Standards [10 CFR 50.55a(h)]	Notification Requirements [10 CFR 50.72, 50.73]

Requirements no longer applicable to RISC-3 SSCs

NRC Special Treatment Requirements **(Current)**	Owner Controlled Alternative Treatments **(New)**
What Licensees Must Do Today to Meet NRC Regulations	What Licensees Determine is the Right Thing to do for Safety and Efficiency
Requirements Defined by NRC	Requirements Defined by Licensee with No NRC Approval
Needs to Provide **Assurance** - More Rigor	Needs to Provide **Confidence*** - Less Rigor

*Still needs to show that the component is capable of meeting its safety functions

The savings associated with implementing 10 CFR 50.69 will be site specific based on plant design, number of systems categorized and alternative treatments implemented. EB 17-09 estimates a reduction between $1M-$3M in parts and maintenance per year for each unit.

What guidance is there for alternative treatments?

Once SSCs for a system (or systems) have been categorized using NEI 00-04, 10 CFR 50.69 SSC Categorization Guidance, plants can remove RISC-3 SSCs from the scope of programs that are no longer applicable. RISC-3 SSCs are discussed in NEI 16-09, Risk-Informed Engineering Programs (10 CFR 50.69) Implementation Guidance, along with some general guidance for each of the requirements that no longer apply.

There are several EPRI reports providing general guidance for alternative treatments. These include:

- Option 2, 10CFR50.69 Special Treatment Guidelines. EPRI, Palo Alto, CA: 2007. 1015099.
- Program on Technology Innovation: 10CFR50.69 Implementation Guidance for Treatment of Structures, Systems, and Components. EPRI, Palo Alto, CA: 2006. 1011234.
- Guidance for Accident Function Assessment for RISC-3 Applications: Alternate Treatment to Environmental Qualification for RISC-3 Applications. EPRI, Palo Alto, CA: 2005. 1009748.
- RISC-3 Seismic Assessment Guidelines. EPRI, Palo Alto, CA: 2005. 1011783.
- Template for Submission of a Risk-Informed Electrical Equipment Qualification Program: Environmental Qualification, EPRI, Palo Alto, CA: 2000. 1000845.

What else is needed to cost effectively implement alternative treatments?

The industry is also working on development of alternative treatment guidance for specific regulatory programs and development of generic tools/templates to streamline and automate documentation and maintenance for utilities.

Structural Integrity's expertise has long involved the prevention of failures of structural and mechanical components using risk insights and probabilistic methods. We have supported implementation of EPRI's risk-informed ISI program at many BWR and PWR plants as well as risk-informed repair/replacement activities. We regularly apply probabilistic analysis to reduce conservatisms where standard techniques are not cost-effective.

With the addition of Tobolski-Watkins to our team see, *(page 25)* and previous additions of Anatech, Finetech and our electrical services group, our core expertise has expanded to every type of component that would benefit from the establishment of alternative treatments.

Beyond these capabilities, Structural Integrity has for decades contributed to the development of EPRI and other industry applications that leverage available technical knowledge and actual plant information to reliably determine the useful life of SSCs in both nuclear and critical non-nuclear applications. The application of tools such as pc-CRACK, SI:FatiguePro, pc-SAFER, LPRimLife, and PlantTrack already contributes to significant cost savings by helping plants avoid unnecessary replacements, defer replacements until a time that allows for a more cost-effective planning and procurement, or to implement other lower cost alternatives.

Our experience with component testing (*TRU Compliance, page 26*) and involvement with industry standards committees provides our experts with useful insights that can be successfully applied to development of alternative treatments having a solid technical basis.

As one of the most trusted independent providers of engineering and technical services, SI looks forward to supporting this important industry initiative.

Metallurgical Lab Featured Damage Mechanism:

Failure of Dissimilar Metal Welds (DMW) in Steam-Cooled Boiler Tubes

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TOP FIGURE 1. Fractured DMW

FIGURE 2. Classic DMW fracture surfaces, which are thick-walled fracture with evidence of low ductility.

Large utility-type steam generators inevitably contain a large number of pressure part welds that join components fabricated from different alloys.

Background

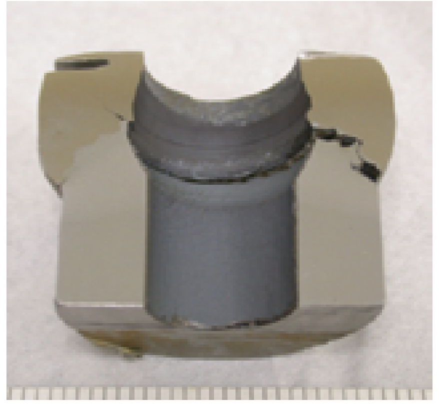
The welds made between austenitic stainless steel tubing and the lower-alloyed ferritic grades of tubing (T11, T22) deserve special mention because of the early failures that developed in some of these dissimilar metal welds (DMWs) soon after their introduction in superheater and reheater assemblies. Prior to the mid-1970s, many DMWs were fabricated either as standard fusion welds using an austenitic stainless filler metal, such as TP308, or as induction pressure welds, in which the tubes were fused directly to each other without the addition of filler metal. Some of these welds failed after less than 40,000 hours of operation, with the earliest failures being associated with DMWs that operated "hot" in units that cycled heavily and were subjected to bending stresses during operation.

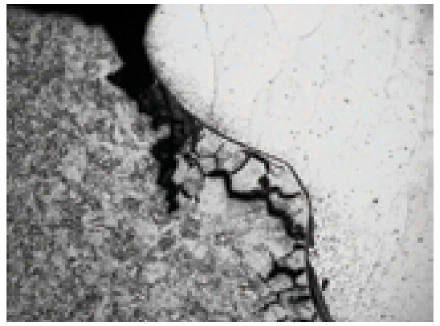
After the mid-1970s, and in response to extensive research carried out by EPRI and other organizations, an increasing number of DMWs in superheater and reheater tubes were fabricated as fusion welds using nickel-based filler metals, such as the INCO A, INCO 82, INCO 182, etc. The technical rationale for the switch to the nickel-based filler metals was the improved compatibility in thermal-physical properties with the lower alloyed materials (typically Grades 11 or 22). It was hoped this would reduce the complex stresses that developed in the lower alloyed material near the dissimilar metal fusion boundary during temperature cycling and that were believed to be an important factor in the early deterioration of the original DMWs.

Other factors that have been shown to influence DMW life are the average temperature of operation and secondary stresses acting on the weld. Subsequent experience has confirmed the relative longevity of the DMWs made with nickel-based filler metals, although that same experience has proven that even these welds will fail at the dissimilar metal interface with the lower alloyed material after prolonged service under certain conditions of stress and temperature. Because of the different metallurgies at the dissimilar metal interface when comparing DMWs made with austenitic stainless filler metal (or the induction pressure type DMWs) and DMWs made with nickel-based filler metal, the evolution of damage in the two types of DMW differs slightly.

Mechanism

For DMWs to low alloy steels (T11, T22), creep and creep-fatigue are the primary damage mechanisms responsible for the failure of DMWs in superheater and reheater tubing, with creep being the dominant component in the damage evolution process. Creep damage is exacerbated by carbon migration that occurs from the low Cr base metal to the high Cr filler metal, resulting in a creep-weak region adjacent to the fusion line. As such, the most important influences on weld life will be the average operating temperature and the magnitude of the stresses acting on the weld. The stresses include primary stresses (i.e., hoop stress and dead weight load), secondary stresses (e.g., bending stresses caused by malfunction of tube supports or by restraint of thermal expansion), and so-called "self stresses" generated along the dissimilar metal interface by the difference in thermal expansion between the austenitic weld metal and ferritic base metal.





TOP FIGURE 3. Crack at ferritic side DMW fusion line.

MIDDLE FIGURE 4. Cross section through crack shown in Figure 3.

BOTTOM FIGURE 5. Oxide notch and creep damage at OD surface at ferritic side fusion zone.

Fusion welds made with austenitic stainless filler metal typically contain damage in the form of creep-induced cavitation and micro-fissuring at grain boundaries in the ferritic material adjacent to the dissimilar metal fusion boundary. Fusion welds made with nickel-based filler metals most often develop damage as cavitation associated with large blocky carbides preferentially aligned along the fusion boundary. The large blocky carbides have been designated "Type I" carbides to distinguish them from the diffuse array of smaller carbides – the "Type II" carbides - that form in DMWs made from both austenitic stainless steel and nickel-based filler metals.

Less commonly, DMWs have failed by a separate damage mechanism involving the initiation and growth of an oxidation-fatigue notch from the toe of the weld on the ferritic side of the joint. These oxide notches, which are fairly common in DMWs and generally have a minimal impact on weld life, can become the life-limiting factor if the tube is relatively thin-walled and if it is subjected to a relatively high bending load.

Typical Locations

Ferritic side of superheater or reheater tube welds that join austenitic stainless material to lower-alloyed ferritic material.

Features (see Figures 1 – 5)

- Circumferential orientation
- Adjacent to DMW in ferritic material
- Thick-walled fracture with evidence of low ductility

The following article summarizes several case studies of damage in DMWs between low alloy steels and stainless steels.

A future article will provide insight into DMWs that involve the Grade 91 alloy, such as welds between P91 piping and 1CrMoV valves or where P91 is welded to stainless steel flow meters. There are some differences between DMW failures in bainitic steels like Grades 11 and 22, and in martensitic steels like Grade 91, so look for that article in a future edition.

Metallurgical Lab:
Dissimilar Metal Welds (DMW) in Boiler Tubing

The need for confirmation: A Case Study

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As plants age, the need for inspection for service related damage to ensure unit reliability increases. There are several approaches that plants can take to reduce the risk of premature failures and proactively manage their DMWs. First is metallurgical sampling. Based on temperature profiles across the boiler, operating conditions, and operating history, DMWs can be selected for laboratory analysis. This will provide some insight into possible damage accumulation; however, the better approach, if damage is suspected, is to perform an ultrasonic inspection of the DMWs. This allows inspection of ***all*** the DMWs, and only requires access and surface preparation. If indications are detected, then tube sampling should be performed. It is critical to perform a metallurgical analysis of several of the DMWs suspected of containing service damage to confirm that the indications are service related and to help establish the extent of the damage compared to ultrasonic testing results. Typical DMW damage is described in the Featured Damage Mechanism article. The importance of the metallurgical analysis is demonstrated in the three following case studies.

Case 1

The boiler had been in service for about 260,000 hours when it experienced a DMW failure. The failed tube was submitted for laboratory analysis, which confirmed the failure was due to creep. Figure 1 shows a cross sectional view of the creep fracture across the DMW and a higher magnification view of the

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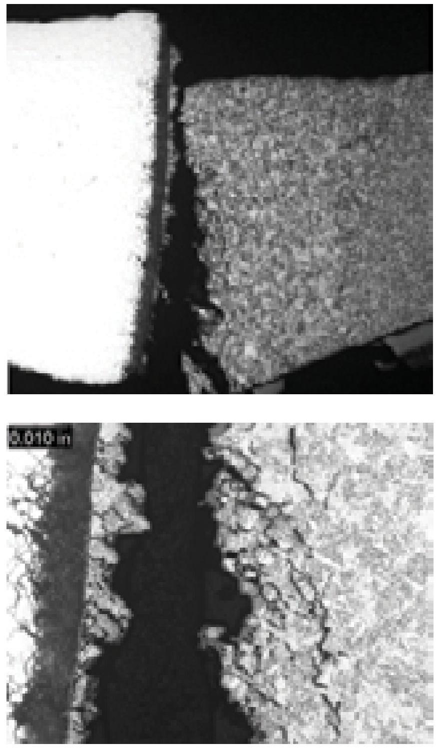

FIGURE 1. Cross sectional views showing creep damage observed in a friction DMW (Etchant: Nital).

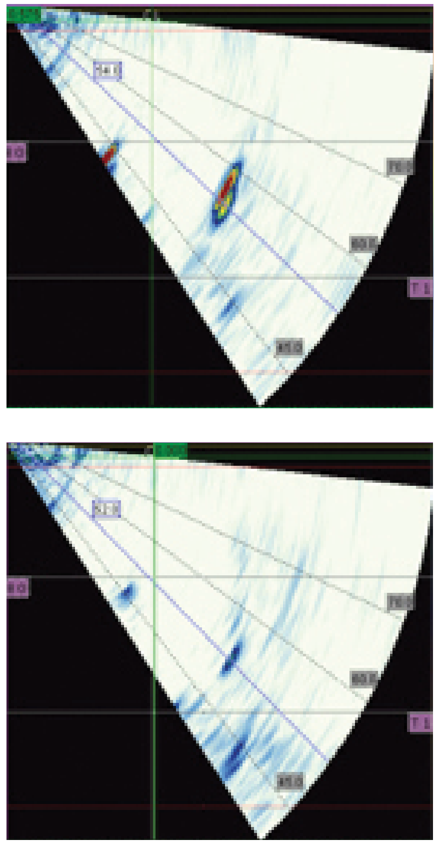

FIGURE 2.
TOP LPA images shows scans from a 25% - 50% classifications
BOTTOM <25% classifications

extensive creep damage in the ferritic material adjacent to the fusion line.

Based on the observed creep damage, the decision was made to perform an ultrasonic inspection of the DMWs during the next scheduled outage. The DMW inspection was performed using linear phased array (LPA) ultrasonic testing. Due to the fact that the DMWs were located in panels, the inspection was limited just to the accessible sides of the tubes. Each DMW was categorized based on the size of the indications relative to the wall thickness. The five categories were no recordable indications (NRI), <25%, 25% - 50%, 50% - 75%, and 75% - 100% through wall. Over 100 DMWs were inspected and four DMWs were identified as containing indications 25% - 50% through wall and eighteen were identified as containing indications <25% through wall. No indications were detected in the remaining DMWs. Figure 2 show the LPA images for one of the 25% - 50% classifications and one of the <25% classifications.

Four samples were removed for metallurgical analysis: two samples containing indications 25% - 50% through wall, one sample containing indications <25% through wall, and one sample containing no indications. Each DMW was sectioned longitudinally at four quadrants

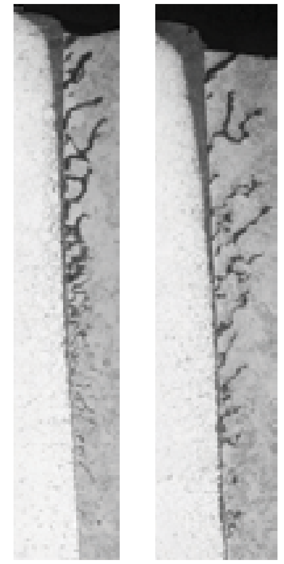

FIGURE 3. Creep damage observed in the ferritic material along the DMW fusion line (Etchant: Nital).

(12:00, 3:00, 6:00, and 9:00). The cross sections were mounted, ground, polished, and etched using standard laboratory techniques. The prepared mounts were examined using a metallurgical microscope for evaluation of service damage associated with the DMWs. Figure 3 shows the typical creep damage observed in the DMWs. The damage extended in the ferritic material adjacent to the weld fusion line from the external surface.

The metallographic results confirmed the damage was service related and agreed with the extent of the

Sample	LPA Results	Metallographic Results	Comments
1	25% - 50%	Extensive creep damage was observed. The damage was 68% through wall	The maximum damage was observed in an area inaccessible during the LPA inspection. Maximum damage at an LPA accessible location was 37%
2	25% - 50%	Extensive creep damage was observed. The damage was 51% through wall	The maximum damage was observed in an area inaccessible during the LPA inspection. Maximum damage at an LPA accessible location was 39%
3	<25%	Total service-related damage was 11% through wall	
4	NRI	No service related damage observed	

TABLE 1. Comparison of LPA Inspection and Metallographic Results for Case 1

Location	Classification				
	0	<25%	25%-50%	50%-75%	75%-100%
Penthouse	56	33	46	23	0
Boiler	88	34	29	5	2

TABLE 2. LPA Inspection Results for Case 2

Sample	LPA Results	Metallographic Results	Comments
P1	50% - 75%	The damage was 28% through wall	Contained lack of fusion and slag inclusions, which resulted in overestimation of creep damage level
B1	50% - 75%	The damage was 54% through wall	Contained lack of fusion along stainless steel fusion line
B2	75%-100%	Extensive creep damage with total service-related damage of 85% through wall	

TABLE 3. Comparison of LPA Inspection and Metallographic Results Case 2

damage detected, as shown in Table 1. In addition, the laboratory analysis revealed more extensive damage in a region inaccessible to the LPA inspection due to the panel configuration.

Case 2

The boiler was commissioned in 1968. The pendant superheat section consisted of 79 pendants with two tubes in each assembly. Dissimilar metal welds connecting Grade TP347H stainless steel to Grade T22 were located on the outlet leg approximately 12 inches above the roof in the penthouse. A second set of DMWs was located in the boiler, 39 inches and 54 inches above the lower bend. A total of 316 DWMs was inspected in the superheater tubing using LPA. Table 2 summarizes the results of the LPA inspection.

Two DMWs were removed from the boiler: one 50%-75% classification and one 75%-100% classification. A DMW from the penthouse with a 50%-75% classifications was also removed. Samples were cut from each DMW at four quadrants and prepared for metallographic examination. Table 3 presents a comparison of the LPA inspection results with the laboratory analysis results.

The LPA classification showed good correlation with the actual amount of creep damage observed in the two DMWs removed from the boiler. The LPA classification for the DMW removed from the penthouse overestimated the actual damage present; however, the DMW contained numerous welding flaws which would also act as signal reflectors. Figure 4 shows lack of fusion and slag inclusions observed in the DMW from the penthouse.

Following the initial LPA inspection, the plant had planned to replace any DMWs with damage greater than 50% through wall. The analysis of the two DMWs from the boiler confirmed the creep damage and the other five DMWs were replaced. However, the relatively large number of DMWs identified as >50% damage in the penthouse was going to cause the outage to be extended. Laboratory analysis of the DMW from the penthouse revealed that the creep damage was not as extensive as initially indicated by the LPA inspection. As mentioned above, the presence of extensive welding flaws (lack of fusion and slag inclusions) provided additional signal reflectors and caused the level of creep damage to appear worse than it was. The absence of any significant damage in the stub tubes suggest that they were not experiencing any

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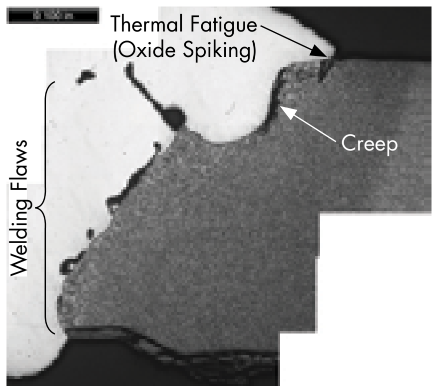

FIGURE 4. Cross sectional view of the DMW removed from the penthouse. The DMW contained extensive welding flaws. Service related damage was also observed (Etchant: Nital).

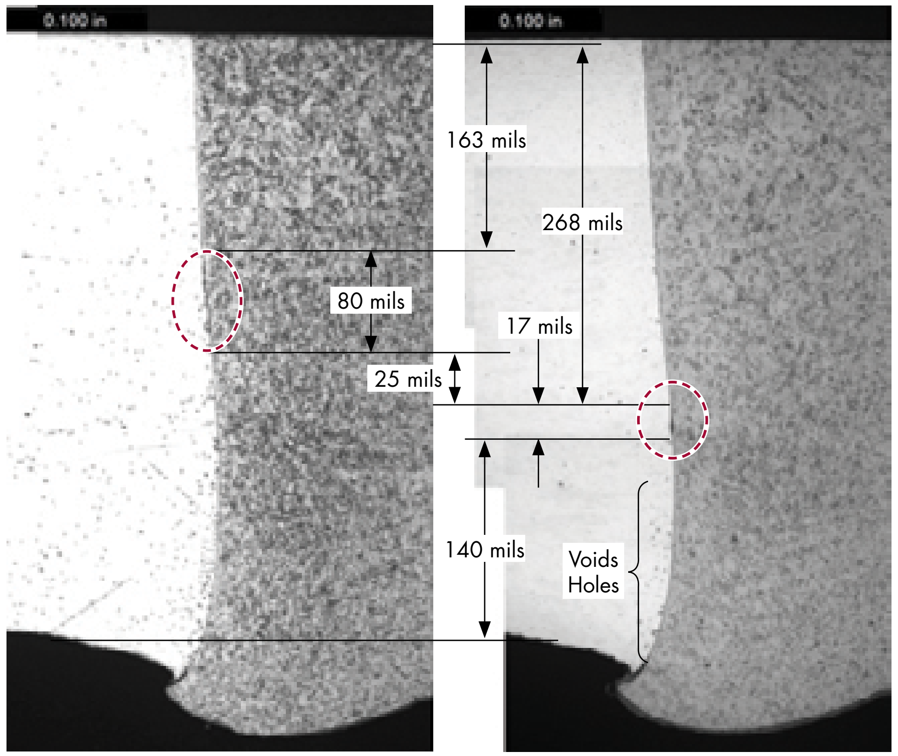

FIGURE 5. Locations and measurements of possible sources of UT reflectors.

appreciable bending loads. The absence of bending loads at the tube-to-header connections suggested that the DMWs in the penthouse were also not experiencing significant bending loads. Based on the above observations and the lower level of creep damage confirmed by the laboratory analysis, replacement of the DMWs in the penthouse was postponed until the next scheduled outage when the repair could be planned as opposed to extending the current outage.

Case 3

The boiler had been in service for about 255,000 hours. As part of a normal condition assessment of the boiler, an LPA inspection of the DMWs in the superheat section was performed by a third party. Reportedly, very few DMWs contained appreciable damage; however, one DMW did contain over 60% through wall damage. The damage was noted from just above the midwall to the internal surface. This sample was submitted to Structural Integrity's Material Science Center for analysis. The location containing the most severe damage had been marked. A section was cut across the DMW about 1/8 inch to the side of the mark and mounted in preparation for metallographic examination. It must be noted that LPA inspection is a volumetric inspection, whereas, metallographic examination looks at a single plane; therefore, in an attempt to examine the DMW volume, progressive polishing was utilized. The sample was progressively polished and examined at 50-mil increments through the marked region. Figure 5 shows two adjacent planes that were examined across the DMW. Both planes revealed several possible sources of the UT indications. It should be noted that the two planes were separated by approximately 50 mils and the position of the indications varied. Comparing the locations and lengths of the various flaws suggested damage extending 62% through wall. The flaws consisted of lack of fusion and slag inclusions at the weld fusion line and debonded inclusions in the stainless steel adjacent to the fusion line.

Minimal service related damage was observed in the DMW with the majority of the UT reflectors likely caused by welding flaws. The presence of welding flaws in this sample explained why the DMWs in the superheat section contained relatively low levels of potential damage detected during the LPA inspection with only a few exhibiting high potential damage levels. Examination of a single polished surface did not show good correlation to the LPA scan image; however, when viewing all the planes together, the metallography revealed good correlation to the LPA scan.

Structural Integrity Acquires Tobolski Watkins Engineering

Acquisition immediately boosts capabilities in advanced structural analysis and equipment certification

May 2017, Structural Integrity expanded its engineering leadership through the acquisition of Tobolski Watkins Engineering, a leading engineering consulting firm based in San Diego, California, along with its product certification company, TRU Compliance, based in Bend, Oregon.

Since its founding in 2008, Tobolski Watkins Engineering (TWE) has earned the trust of a wide range of clients for its services in structural, earthquake, and blast engineering of critical systems and facilities. TWE has routinely developed creative and robust engineering solutions to resist extreme event loading in industries such as nuclear power and defense, as well as for industrial, healthcare and government facilities. Key service offerings include: structural engineering, earthquake engineering, advanced analysis for extreme loading and anti-terrorism force-protection consulting. TWE complements Structural Integrity's advanced structural capabilities by providing non-linear analysis in evaluating impacts from load drops to tornado borne missiles; fluid/structure interaction (FSI); and soil/structure interaction (SSI) for safety related facilities, structures, and equipment. Through TRU Compliance, TWE's highly respected product certification brand, seismic, wind, and blast certifications are delivered for critical utilities and building systems, with emphasis on shake table testing and finite element analysis.

"We look forward to integrating their innovation, resources and skills within the Structural Integrity organization by combining our structures groups along with TRU Compliance into a new Business Unit – Critical Structures and Facilities", said Laney Bisbee, CEO of Structural Integrity. "Their mission, goals, and values for innovative solutions and top quality service closely match ours to make this expanded service beneficial to all clients."

Moving forward, TWE engineers will continue to deliver industry-leading client service and technical solutions as part of the larger Structural Integrity team. "It isn't often that I find a consulting engineering firm so well aligned with our culture, values, focus on innovation and commitment to the success of our clients", said Matt Tobolski, PhD, SE. "I am personally excited to be part of the SI team and continue to deliver quality solutions that solve some of the industry's most challenging problems. By combining forces, we will be able to offer expanded solutions to our clients and tackle larger projects throughout the world."

> "Their mission, goals, and values for innovative solutions and top quality service closely match ours to make this expanded service beneficial to all clients."

Through the acquisition of Tobolski Watkins Engineering Structural Integrity will expand its presence San Diego, CA as well as have new-found presence in Bend, OR.

TRU Compliance:

The Standard for Seismic, Wind, and Blast Certification

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About TRU COMPLIANCE

As the product certification arm of Structural Integrity, TRU Compliance stands for safety and code compliance when failure is not an option. Our clients manufacture cutting edge products that push the limits of operational performance and efficiency in many industries. We help them achieve continued performance during earthquakes, high wind events, explosions, and a host of other extreme events.

At TRU Compliance, we believe that achieving code compliance in these areas should not be complicated. So, we continually invest in the development of innovative systems and approaches to simplify the lives of our clients and deliver efficient and transparent results, every time.

Product Certification Agency

TRU Compliance is a recognized leader in Seismic, Wind & Blast product certification. We are a full-service product certification agency executing project specific and product line approvals for a range of code requirements. The TRU Compliance team has been providing product certification services since 2008 and recently joined forces with Structural Integrity in May 2017, thus expanding our resources and reach.

TRU Compliance product certification provides customized, turn-key product certification programs tailored to meet our clients' unique needs. Our staff has extensive experience in code development, project execution and peer review. Certification programs are founded on technically defensible approaches that satisfy the most stringent requirements and reviews.

You can trust in TRU Compliance and our commitment to be a transparent product certification agency. With over 15,000 individual product certifications to date and even more internal subcomponents, TRU Compliance knows what it takes to effectively execute projects.

Seismic Certification

Our seismic team provides a streamlined approach to certification or qualification of equipment for use in critical facilities such as nuclear plants, electrical substations, ambulatory care hospitals, and emergency response centers. These assets serve a critical function that must be maintained during and after an earthquake.

Following industry codes and standards such as IEEE 323/344, IEEE 693, ICC AC156, and ASCE 7, we certify a seismic rating for even the largest, most complex equipment using our network of accredited test labs and/or our industry leading engineering analysis tools.

TRU COMPLIANCE

TRU COMPLIANCE LISTED

TRU COMPLIANCE SEISMIC

TRU COMPLIANCE WIND

TRU COMPLIANCE BLAST

Wind Certification

Our wind certification services provide hurricane, tornado, and windstorm testing and analysis to the latest codes and standards to certify products and keep them fastened when the storm hits. Whether certification is achieved from windborne debris, static pressure, or wind tunnel testing or whether an application requires a detailed wind analysis, we help our customers achieve the wind ratings they need to get their products approved on any project.

Blast and Impact

Blast and physical security testing and analysis covers products protecting military, civilian, and industrial facilities from terrorism or accidental explosion. Windows, doors, wall systems, and vehicle barriers are often required to meet stringent government standards and require carefully crafted combinations of testing and project-specific analysis. We help our clients' products achieve compliance with these standards through our network of test facilities including explosive ranges, shock tubes, ballistic ranges, and crash facilities.

TOP Air Handling Unit Awaiting Seismic Testing

MIDDLE Electrical Subomponents

BOTTOM Live Explosive Blast Testing

Harsh Environments (NEW)

Since TRU Compliance joined Structural Integrity in 2017, we have begun integrating SI's services for harsh environment certification of electrical component for critical facilities. Our team in the Electrical Services Group (formerly Engineered Solutions Group) is a great solution for OEMs and utilities looking for the right qualification plan for stringent harsh environment specifications.

Experience the TRU difference at *TRUCompliance.com*.

Using Falcon to Develop RIA Pellet-Cladding Mechanical Interaction (PCMI) Failure Criteria

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Introduction

The goal to achieve higher fuel rod burnup levels has produced considerable interest in the transient response of high burnup nuclear fuel. Several experimental programs have been initiated to generate data on the behavior of high burnup fuel under transient conditions representative of Reactivity Initiated Accidents (RIAs). A RIA is an important postulated accident for the design of Light Water Reactors (LWRs). It is considered the bounding accident for uncontrolled reactivity insertions.

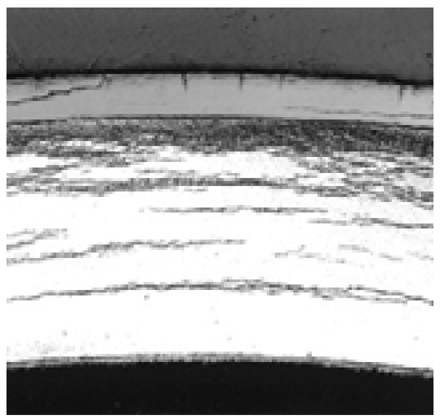


FIGURE 1. Example of the microstructure of a high burnup fuel cladding sample.

The initial results from RIA-simulation tests on fuel rod segments with burnup levels above 50 GWd/tU, namely CABRI REP Na-1 (conducted in 1993) and NSRR HBO-1 (conducted in 1994), raised concerns that the licensing criteria defined in the Standard Review Plan (NUREG-0800) may be inappropriate beyond a certain level of burnup. Figure 1 is an example of a typical high burnup fuel cladding showing the oxidized and hydrided cladding of higher burnup fuel rods. Figure 2 shows the typical radial crack path in oxidized and hydrided cladding, subjected to RIA simulation tests. As a consequence of these findings, EPRI with the assistance of the Structural Integrity's Nuclear Fuel Technology Division (formally ANATECH) and other nuclear industry members conducted an extensive review and assessment of the observed behavior of high burnup fuel under RIA conditions. The objective was to conduct a detailed analysis of the data obtained from RIA-simulation experiments and to evaluate the applicability of the data to commercial LWR fuel behavior during a Rod Ejection Accident (REA) or Control Rod Drop Accident (CRDA). The assessment included a review of the fuel segments used in the tests, the test procedures, in-pile instrumentation measurements, post-test examination results, and a detailed analytical evaluation of several key RIA-simulation tests.

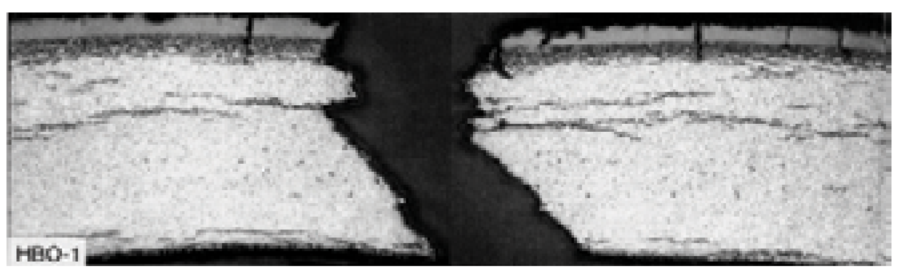
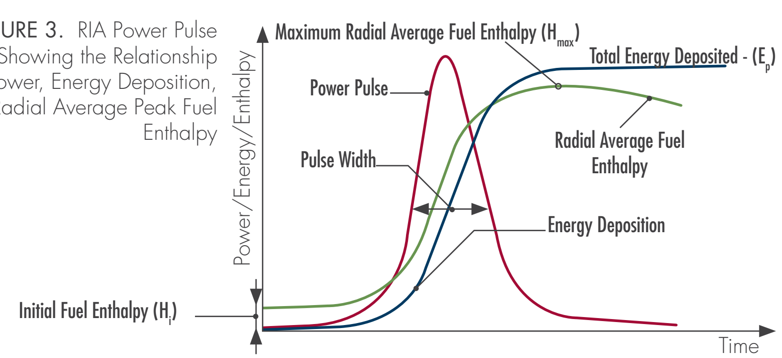


FIGURE 2. Typical radial crack path in oxidized and hydrided cladding, subjected to RIA simulation test in the NSRR.

FIGURE 3. RIA Power Pulse Schematic Showing the Relationship between Power, Energy Deposition, and Radial Average Peak Fuel Enthalpy



This postulated accident results from an inadvertent insertion of reactivity due to the ejection of a control rod assembly in a Pressurized Water Reactor (PWR) or the drop of a control blade in a Boiling Water Reactor (BWR). In the unlikely event that sufficient reactivity is inserted into the reactor core by the ejected/dropped control rod, prompt energy deposition into the fuel can occur, which when sufficiently high can lead to fuel rod failure or, at large energy deposition levels, expulsion of UO_2 fragments or molten UO_2 material from the fuel rod. Requirements to mitigate the consequences of an RIA are specified within the regulations used to license and operate LWRs.

The schematic in Figure 3 highlights the relationships between the power pulse, the energy deposition and the radial average fuel enthalpy. The energy deposition represents the integration of the power-time curve and reaches the total energy deposited once the power returns to zero. The radial average fuel enthalpy is calculated based on the UO_2 specific heat and the radial temperature profile. A maximum is reached near the late part of the power pulse as heat conduction effects begin to dominate. The relative response of these different parameters depends on the pulse width defined by the full-width half maximum (FWHM) of the power pulse.

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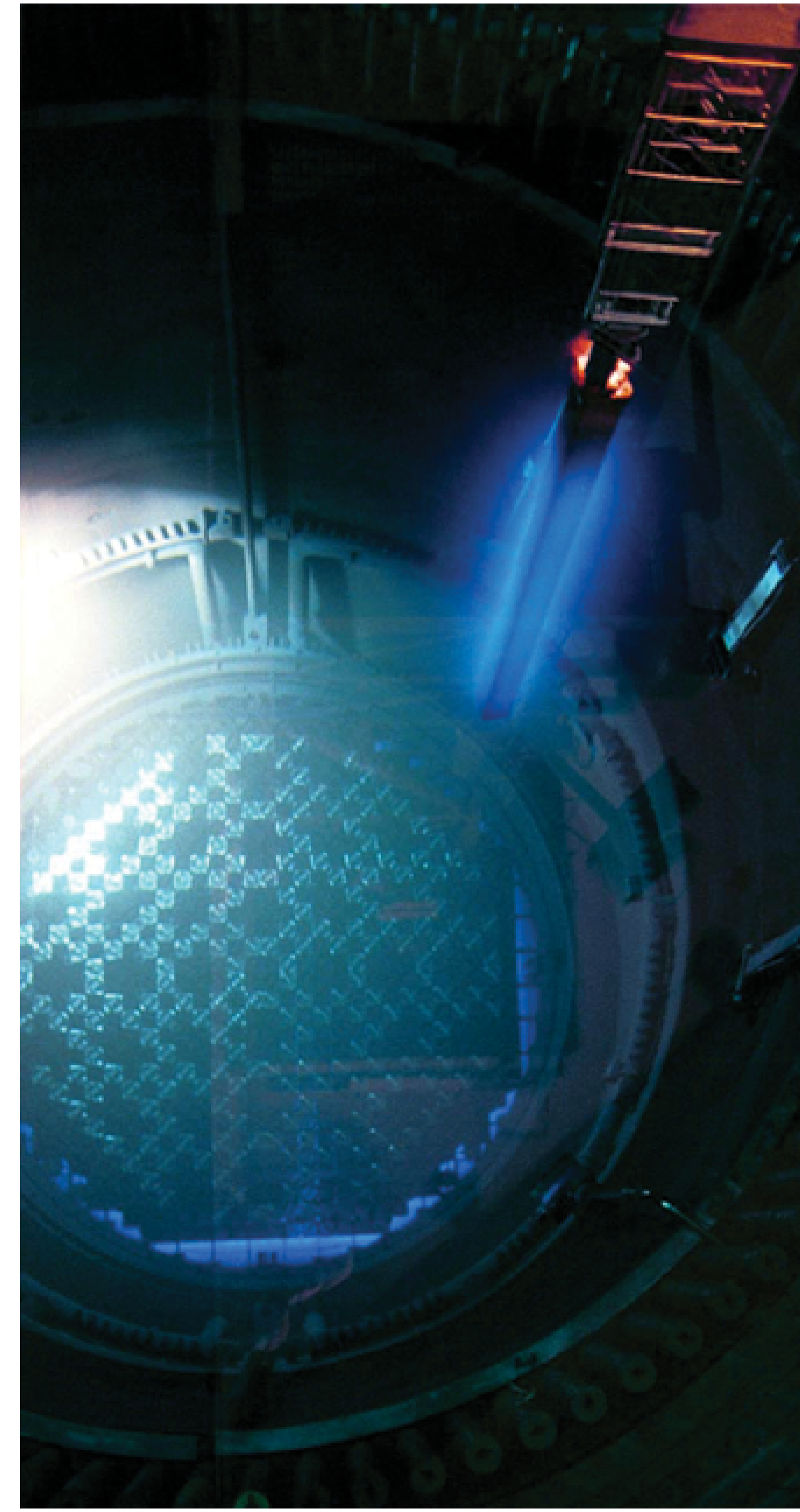

It was also found that the RIA-simulation test conditions are not representative of those expected during a postulated in-reactor REA or CRDA. The experiments were conducted either in room-temperature, atmospheric-pressure water or in hot sodium coolant. The pulses were considerably more rapid (sharper and narrower) than anticipated LWR power pulses calculated using 3-D spatial kinetics methods. Additionally, in many cases, the conditions under which the test rods were base-irradiated produced cladding corrosion and hydriding features that were not representative of commercial LWR fuel. Therefore, analytical evaluations and separate effects data were required to understand the key mechanisms operative in RIA-simulation tests and to translate the experimental results to LWR conditions and different cladding materials. The key finding of the assessment was that loss of cladding ductility, due to increased localized hydrogen content, was the major cause of failure for high burnup test rods during the RIA-simulation tests.

The results from RIA-simulation experiments performed to evaluate the transient behavior of high burnup fuel have shown that the original fuel rod acceptance criteria defined in NUREG-0800 may be insufficient to insure compliance with safety requirements beyond a certain level of burnup for some postulated reactivity-initiated transients. In response to these observations, Section 4.2 of the Standard Review Plan [NUREG-0800] was amended by the NRC to include interim guidance for RIA events. Appendix B, Interim Acceptance Criteria and Guidance for the RIA was included in Revision 3 of the SRP.

As a logical next step in the process, the Regulatory Technical Advisory Committee (Reg-TAC) of the EPRI-sponsored Fuel Reliability Program, with the Nuclear Fuel Technology Division's assistance, developed a strategy to resolve the RIA licensing issues raised by the RIA-simulation experiments and the publication of the interim criteria in NUREG-0800, Section 4.2, Appendix B, Revision 3. The approach employed to develop the suggested revised licensing criteria combined elements of experimental data and analytical evaluations to establish a fundamental understanding of fuel behavior during RIA events. This approach was comprised of three major components:

1. Establishing the transient behavior of intermediate and high burnup fuel rods using well-characterized RIA simulation tests. The RIA-simulation experiments in the previous evaluation, and the more recent tests on rods with burnup levels ranging from 45-77 GWd/tU in CABRI and NSRR, provided a database of in-pile observations and post-test examinations that can be used to evaluate the phenomena and mechanisms that influence the transient performance of the fuel and cladding under these conditions.
2. Defining the cladding mechanical properties using data from separate effects tests. The database of Zircaloy cladding mechanical properties furnished insights into the influence of irradiation damage, hydrogen content and distribution, and temperature on the capability of the cladding to accommodate the pellet loading during an RIA event.
3. Benchmarking the RIA analysis capabilities with Falcon using experimental data from the database of RIA-simulation tests. Performing fuel rod analyses of the RIA experiments provides a means to validate the predictive capabilities of the program and provides insights into the mechanisms that influence the pellet and cladding transient performance.

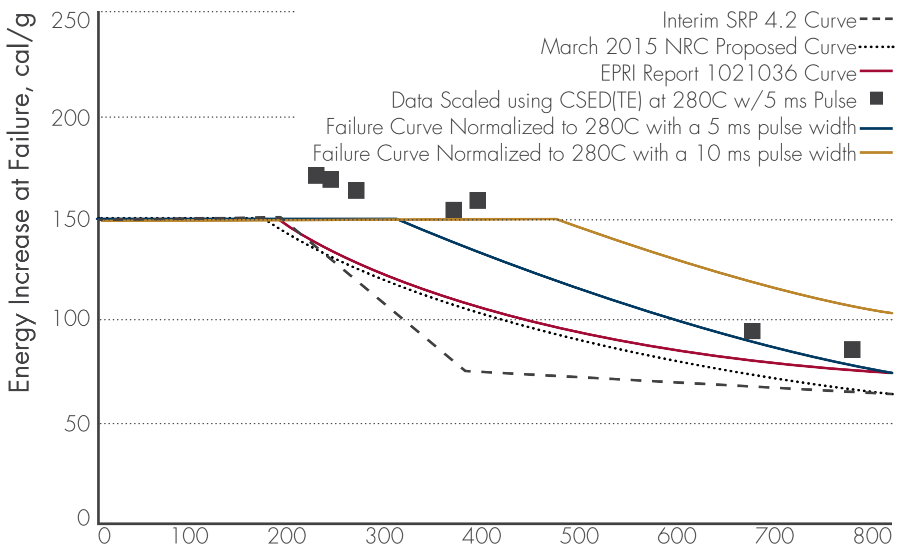

FIGURE 4. Proposed increase in the interim failure criteria for HZP conditions based on the Falcon SED/CSED approach.

Detailed fuel behavior analyses were performed by Structural Integrity for key RIA-simulation experiments using the EPRI fuel behavior code Falcon. These analyses were based on the CSED/SED approach presented in Reference 1. Starting from room temperature and atmospheric pressure, reactivity insertion leads to a very short power pulse in the test rod. The energy deposited in the fuel causes the fuel to expand and close the gap very quickly. With further energy deposition and fuel expansion, the cladding is strained and at the peak power, the combination of high strain rate and relatively lower cladding temperature gives rise to the strong constraint on the cladding. After that, though the fuel is still expanding, the cladding yield stress starts to decrease; as a result, peak hoop stress is achieved. Since the mechanical load is driven by fuel thermal expansion, which correlates to the total energy deposited in the fuel, both the peak hoop stress and the maximum Strain Energy Density (SED) are reached in the pulse phase. Cladding mechanical properties are then used to develop the Critical Strain Energy Density (CSED) required to initiate material failure based on mechanical property tests conducted with irradiated Zircaloy cladding. The CSED is represented as a function of the material condition, temperature, and loading state. An increase in the potential for cladding failure is assumed to occur at the point where the Falcon calculated SED exceeds the CSED for the given cladding condition defined by temperature and hydrogen content. These analyses were then used to calculate scaling factors to adjust experimental data generated at non-prototypic cold reactor coolant conditions and pressures to hot power conditions.

For the PWR hot zero power conditions, the scaled test results are presented in Figure 4 and compared to the interim NRC criterion. These data points were then fit to generate a failure enthalpy limit as a function of hydrogen.

However, it is possible for BWR CRDA to occur when the coolant temperature is near ambient conditions. Nevertheless, operating history shows that most of the time during startup criticality occurs at 50°C or higher. Although an RIA event can occur prior to core wide criticality, such an event early in core startup will not result in significant energy deposition because the reactivity increase from such an event needs to first overcome the reactivity difference to core wide criticality before any energy deposition can take place (control rods are withdrawn in banks and core wide critically is reached gradually). Also, considering that the neutronics associated with CRD events results in pulse widths on the order of 20 ms or more, the mid-wall cladding temperature would experience an increase of approximately 50°C. Therefore, the cladding temperature for BWR events will be on the order of 80°C or higher. Mechanical property tests show that the ductile/brittle transition begins at approximately 60°C to 70°C and is dependent on the loading rate. For temperatures >85 °C and pulse widths > 15 ms, the cladding material is shown to be ductile and therefore failure by PCMI is not likely below injected enthalpies of 150 cal/g. For ambient temperature conditions, the SED/CSED approach with Falcon was used to determine the enthalpy increase associated with scaling the room temperature NSRR data to pulse widths of 5ms and > 15ms. The increased enthalpies accounting for the loading rate effect are presented in Figure 5.

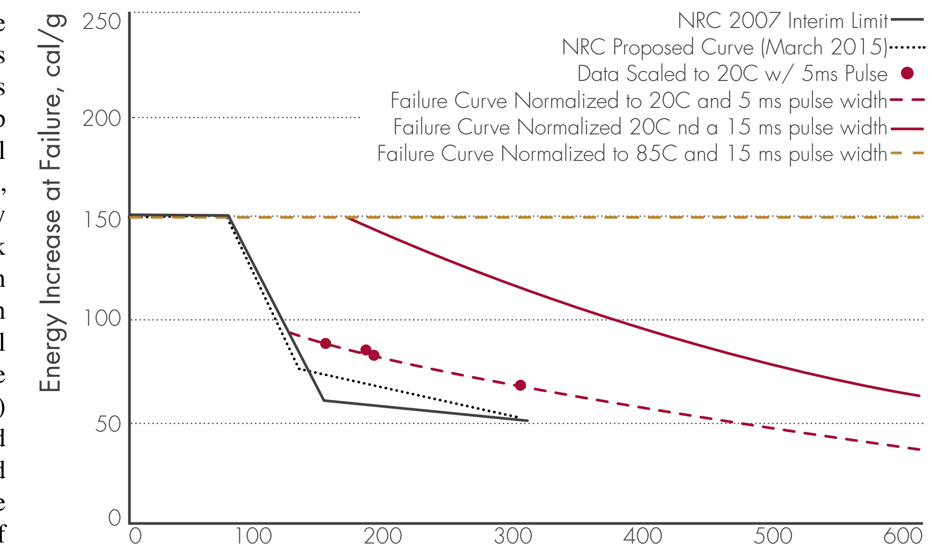

FIGURE 5. Proposed increase in the interim failure criteria for HZP conditions based on the Falcon SED/CSED approach.

The overall fuel rod failure threshold was obtained by combining the high temperature failure threshold of 150 cal/gm with the fuel enthalpy required to produce cladding failure by PCMI as determined by the analytical evaluation. The decrease in the failure threshold is caused by two factors, the increase in PCMI loading due to gap closure effects at higher fuel rod burnups and by the decrease in cladding ductility with hydrogen accumulation. Pulse width and temperature were found to be the two factors that improve cladding ductility and therefore improving PCMI loading resistance. These results demonstrate the capability of the methodology to conservatively model the complex thermal and mechanical behavior of high burnup fuel during rapid energy depositions corresponding to a RIA event. Applying fuel cladding mechanical properties at commercial reactor conditions significantly increased the ability of the fuel to absorb energy without failure during a RIA. These new RIA PCMI acceptance criteria have been proposed for the final version of the interim RIA failure criteria for PCMI processes still under consideration by the NRC staff.

Acknowledgments
This work was conducted under the auspices of and with the support of the Regulatory Technical Advisory Committee of the EPRI Fuel Reliability Program.

References

[1] Fuel Reliability Program: Proposed Reactivity Insertion Accident (RIA) Acceptance Criteria, Revision 1. EPRI, Palo Alto, CA: 2015. 3002005540.

LATITUDE™

Innovating the NDE Data Acquisition Process

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From the creation of the first simple stone tools to the invention of the world wide web, technological innovation has been the undercurrent that has carried the human species from our primitive survivalist ways to our present-day complexity of modern conveniences. We innovate from necessity, competition, or from a desire for an improved quality of life. Innovation has been and remains key to our survival and proliferation.

In business, it is no different and innovation has been a mainstay at Structural Integrity and part of our core values since our inception in 1983. We are constantly developing and applying innovative practices and technologies to meet our clients' toughest challenges and to provide best-in-value solutions. In this spirit, we are excited to announce one of our most recent innovations, LATITUDE™.

What is LATITUDE?

LATITUDE is a non-mechanized position and orientation encoding technology designed for use with nondestructive evaluation (NDE) equipment. Simply stated, LATITUDE enables an operator to manipulate a probe by hand while maintaining a digital record of the position and orientation of the probe at all times. For many applications, LATITUDE can be thought of as a fast and compact alternative to cumbersome and complicated automated inspection equipment.

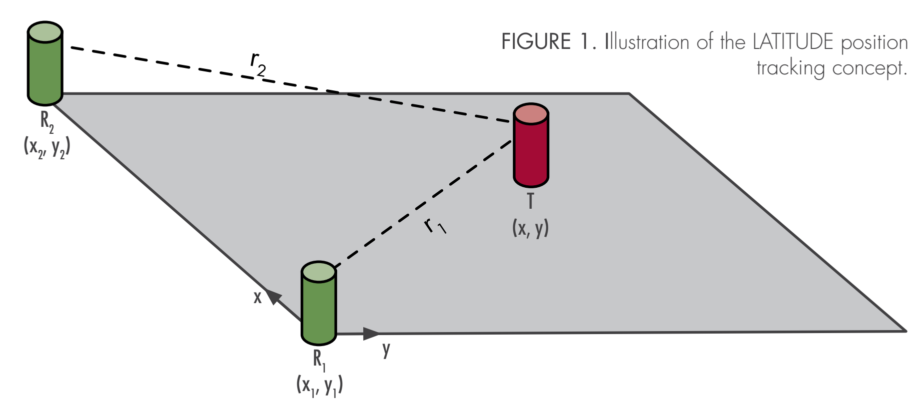

FIGURE 1. Illustration of the LATITUDE position tracking concept.

To replace all the tracks, motors, motion controllers, probe carts, and other equipment used for traditional automated inspections, the LATITUDE system uses air-borne ultrasound to track the position of a transmitting probe relative to a set or array, of stationary receiver sensors. In this way, the LATITUDE transmitting probe can be attached to any of a variety of NDE probes and the absolute position of the NDE probe can be tracked multi-dimensionally. Currently, the LATITUDE system can track x (axial) position, y (circumferential) position, probe rotation (skew), and can compensate for pipe geometry.

The LATITUDE tracking concept is illustrated in Figure 1. The two green cylinders (R_1 and R_2) in Figure 1 represent the air-borne ultrasound receivers and the red cylinder (T) represents the air-borne ultrasound transmitter. The transmitter emits an ultrasonic pressure pulse that can be envisioned to travel along paths r_1 and r_2 to Receiver R_1

Continued on next page

and Receiver R_2, respectively. By measuring, with microsecond accuracy, the time it takes for the ultrasonic pulse to travel along both paths, the relative location of the transmitter can be determined by multiplying the time-of-flight measurement by the speed of sound in air. LATITUDE completes this calculation hundreds of times per second, providing a real-time absolute position measurement. With this type of "absolute" position measurement, the probe can be removed from the pipe surface, placed in a different location, and the system will always know the true position of the probe. It does not rely on accumulated encoder "counts" to estimate the position, like traditional scanning systems.

The LATITUDE system consists of three primary components: (1) the transmitter probe fixture, (2) the receiver array, and (3) the electronic control unit. For the case of Phased Array Ultrasonic Testing (PAUT), the electronic control unit directly integrates with the Zetec TOPAZ™ PAUT instrument and control of the LATITUDE system is done through the TOPAZ user interface. The enclosure is sealed, fanless, and can run for up to 12 hours off two hot-swappable batteries, eliminating the need for a 120V power supply.

The receiver array consists of conformable collar that is wrapped around the pipe circumference or stretched along the pipe axis, depending on the application. All wiring for the receiver array is contained within the array housing, with a single connection point to the LATITUDE electronics. While the receiver arrays have been designed to achieve full circumferential coverage on specific pipe diameters, any receiver array may be used for partial coverage on pipe diameters that are larger than the nominal diameter of the receiver array, up to a flat surface.

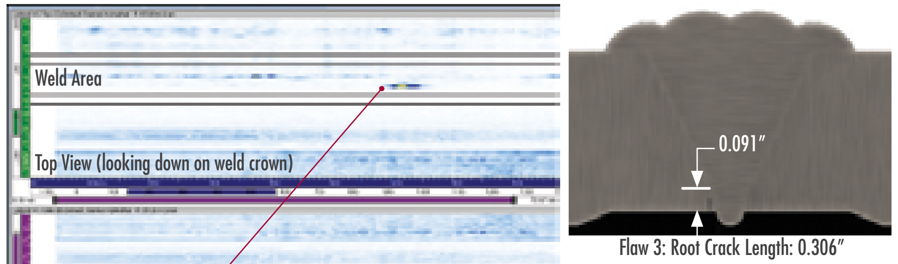

Figure 2. LATITUDE encoded PAUT scan of a girth weld containing a root crack.

The LATITUDE transmitter probe fixture contains multiple sensors for determining the axial position, circumferential position, and skew of the fixture. It is typically affixed to an NDE sensor that is being used to conduct an examination, such as a PAUT probe, an eddy current testing (ECT) probe, or any of several other kinds of NDE sensors.

Why Use LATITUDE?

On one end of the spectrum, manual NDE examinations are relatively simple, quick, and do not require any ancillary equipment; however, there is typically no detailed digital record of the NDE data created, meaning that the NDE data is not available for secondary analysis or future reference, if desired. On the other end of the spectrum, fully automated NDE examinations provide a detailed digital record of the examination that can be reviewed and digitally stored for future reference. However, the data acquisition process is much more complicated, requires much more specialized equipment, and the overall examination process typically takes much longer. LATITUDE provides a compromise between these two extremes, minimizing the amount of additional equipment and set-up required while providing a spatially encoded digital record of the examination data.

Relative to automated inspection equipment, several of the primary advantages of a LATITUDE encoded manual examination are:

- Significantly reduces the average time spent per inspection location
- Enables the creation of a digital record of the NDE data that can be used for future reference
- Reduces the number of personnel required for scanning and data acquisition
- Drastically reduces the amount of equipment needed for examinations
- Battery power eliminates the need for a 120V power source.
- Portability and compactness allows quick setup and breakdown when moving between inspection locations

LATITUDE transmitter attachment on a dual-Matrix PAUT Probe

Typical Applications

LATITUDE is simply a position tracking technology and, as such, can be applied to encode the position of many different types of NDE probes. Initially designed for application to pipe ranging from 6" to 36", the first applications of the technology have been focused on ultrasonic weld examination and corrosion mapping.

In the nuclear industry, Section XI Automated PAUT exams of Dissimilar Metal Welds (DMWs) currently require the use of robotic scanner mechanisms to deliver automated PAUT examinations, which have proven to be both expensive and time-consuming. SI is currently working toward a qualified inspection procedure that incorporates the LATITUDE system to significantly reduce the amount of equipment and number of personnel needed to deliver these encoded examinations. Other weld examination examples where LATITUDE can be used to quickly encode manual scans include UT in lieu of RT and High Energy Piping (HEP) examinations. Figure 2 shows an example of a LATITUDE encoded PAUT scan that was acquired on a girth weld with a 0.306" long, 0.091" deep root crack.

Corrosion mapping is another application that has significant potential to benefit from a LATITUDE encoding approach. When combined with a large-aperture corrosion mapping PAUT probe, critical areas can be mapped very quickly without the need for overly complex probe fixtures, inaccurate string encoders, or slippery encoder wheels. Figure 3 shows an example of a corrosion map that was generated with a corrosion mapping PAUT probe encoded with the LATITUDE system. The entire area (~ 1 sq ft) was mapped in approximately 30 seconds.

These are just several examples of the many possible applications of our new LATITUDE position encoding technology. If you believe that you have an application that could benefit from having a permanent data record or a situation in which automated scanning technologies are simply too bulky or costly, contact Structural Integrity today to discuss the possibilities of a LATITUDE encoded examination.

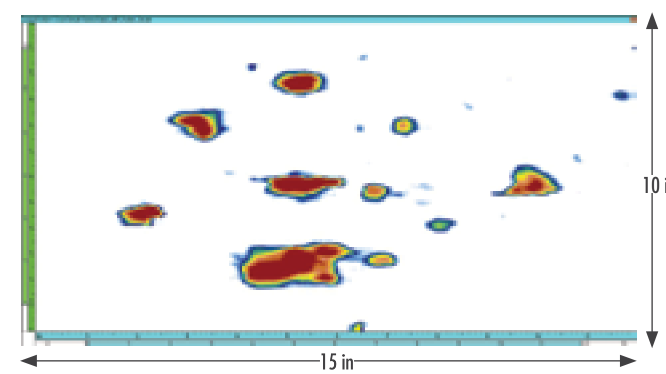

Figure 3. LATITUDE encoded corrosion map of an internally pitted pipe.

LATITUDE transmitter and receiver collar

LATITUDE Technical Specification

Axial Resolution	0.05 in (1.3 mm)
Axial Position Accuracy	±0.118 in (± 3 mm)
Circumferential Resolution	0.05 in (1.3 mm)
Circumferential Position Accuracy	±0.118 in (± 3 mm)
Skew Resolution	1°
Skew Accuracy	±3°
Axial Scan Range	6 in (152 mm)
Circumferential Scan Range	Full Circumference
Max. Scan Speed	2 in/s (50 mm/s)
Battery Life	10 hrs (hot swappable)
Diameter Range	> 6 in
Radial Clearance	2 in
Axial Clearance	4 in

A Strategic Approach for Completing Engineering Critical Assessments of Oil and Gas Transmission Pipelines

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Regulatory Overview

In January 2012, the Pipeline Safety, Regulatory Certainty, and Job Creation Act of 2011 was signed into law directing PHMSA to take steps to further assure the safety of pipeline infrastructure. PHMSA issued the related Notice of Proposed Rulemaking (NPRM) for Safety of Gas Transmission and Gathering Pipelines on April 8, 2016. Included in the NPRM were significant mandates regarding:

- Verification of Pipeline Material (§192.607); and
- Maximum Allowable Operating Pressure (MAOP) Verification or "Determination" (§192.624)

The NPRM proposes requirements for operators to verify the MAOP of a gas transmission pipeline when:

1. The pipeline has experienced an in-service incident (as defined by §191.3) due to select causes[1] in a High Consequence Area (HCA), "piggable" Moderate Consequence Area (MCA), or Class 3 or 4 location since its last successful pressure test
2. The pipeline lacks Traceable, Verifiable, and Complete pressure test records for HCAs or Class 3 or 4 locations
3. The pipeline MAOP was established by the grandfather clause (§192.619 (a)(3)) for HCAs, "piggable" MCAs, or Class 3 or 4 locations.

To verify the MAOP of a pipeline, the NPRM provides the following options:

- **Method 1:** Pressure Test
- **Method 2:** Pressure Reduction
- **Method 3:** Engineering Critical Assessment (ECA)
- **Method 4:** Pipe Replacement
- **Method 5:** Pressure Reduction for segments with small potential impact radius (PIR) & diameter
- **Method 6:** Use Alternative Technology

The ECA Approach

Per the NPRM, Method 3 (ECA) is defined as an analysis, based on fracture mechanics principles, material properties, operating history, operational environment, in-service degradation, possible failure mechanisms, initial and final defect sizes, and usage of future operating and maintenance procedures to determine maximum tolerable sizes for imperfections. Although this analysis may seem daunting, analytical tools and systematic approaches can greatly simplify and enable an efficient, robust, and defensible analysis for completing MAOP verification via the ECA process.

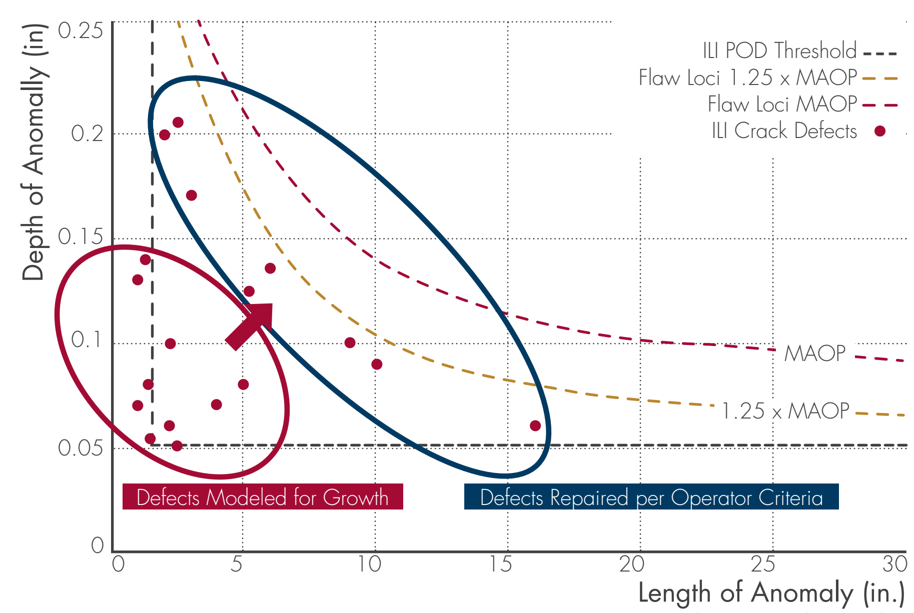

FIGURE 1. Flaw Loci and Anomalies

Fundamental approach and workflow

Structural Integrity has developed a simplified approach to completing ECA that consists of the following:

- Pre-assessment: Completing a detailed review of the material properties (incorporating mill/design/construction records as well as data from a Material Verification program as expected to be required under §192.607); construction practices and operational history of the segment
- Field Data Collection: Utilizing past pressure test, ILI, field inspection records to identify the worst case set of flaws that may currently exist in the pipeline
- Analysis: Implementing a flaw growth model and evaluating the predicted failure pressure with safety factor over time for the specific pipeline characteristics, and estimating safe remaining life of the pipeline assets for a given MAOP.

The proposed ECA process can help improve safety margins and provide further insight into the remaining life of the pipeline by evaluating the range of flaws that may exist, developing an understanding of the key material properties, modeling the rate of degradation and estimating time to failure and safety factors as a function of time using fracture mechanics principles.

To illustrate this in an example, take the case where an operator is missing pressure test records and decides to conduct an ECA to verify MAOP. In this example, pre-assessment record review indicates that the line has a history of Stress Corrosion Cracking (SCC), no prior pressure test and the operator wanted to confirm a safe operating pressure following an EMAT ILI (inspection) run using the ECA process. Assume the pipeline has an outer diameter of 24", a nominal wall thickness of 0.344" and Specified Minimum Yield Strength (SMYS) of 60,000 psi. Based

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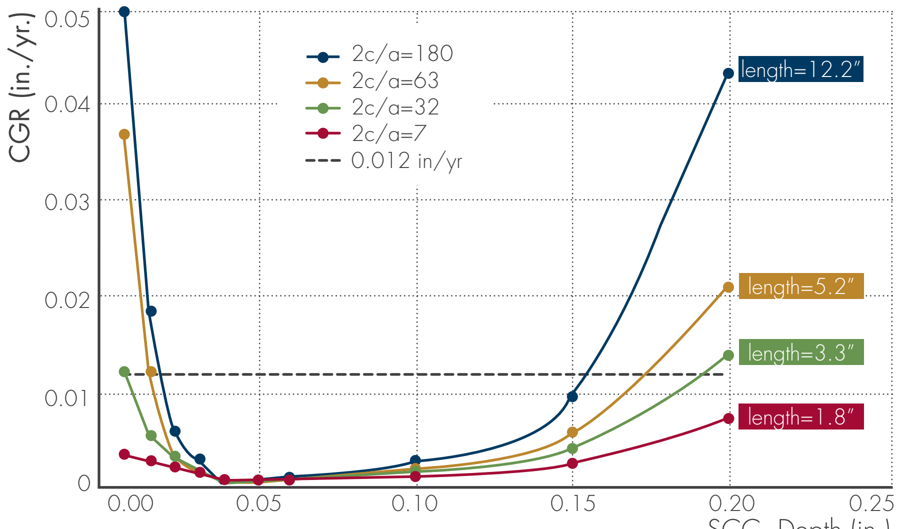

FIGURE 2. SCC Flaw Growth

on selecting a 90th-percentile value from mill reports, a full size CVN value of 31 ft-lbs was used with the modified In-secant method for evaluating predicted failure pressure. The crack-like threats to be evaluated are SCC and crack-like manufacturing defects.

The field data collection phase consists of EMAT ILI combined with a caliper tool to detect dents and possibly Magnetic Flux Leakage for metal loss characterization. Figure 1 provides a set of flaw loci illustrating the set of flaws (length vs depth) that would fail at MAOP (red curve) and at a pressure test at 1.25 x MAOP for the example pipeline. The red data points are hypothetical crack-like flaws detected by the EMAT ILI. Depending on the operator excavation criteria, some or all of these may be repaired. Defects below or to the left of the black curve (ILI Probability of Detection (POD) threshold) will not be detected reliably and must be assumed to exist for analysis purposes.

In the analysis step, growth models can then be applied to the remaining flaws depending on the degradation type. For example, for Electric Resistance Welded seam defects, a fatigue analysis based on Paris Law fatigue growth can utilize past Supervisory Control and Data Acquisition (SCADA) data to estimate crack growth as a function of time. For SCC defects, SI has developed a bathtub growth curve model based on published research (see Figure 2) that incorporates pressure cycle data in addition to Cathodic Protectionlevels and other environmental data.

The possibility of interacting defects must be considered as part of MAOP verification using ECA. Using the detection sensitivities of various tools employed, the "worst case" interacting defects can be evaluated to determine predicted failure pressure for different scenarios and then used to verify MAOP. Alternately, a probabilistic methodology can be employed, taking into account the frequency of occurrence for various defect types and distribution of defect parameters. The probabilistic approach tends to be advantageous due to the extremely low likelihood of the conservative 'worst case' threat interaction scenario (e.g. worst case dent, corrosion, seam anomaly and SCC at the same location).

> "Per the NPRM, Method 3 (ECA) is defined as an analysis, based on fracture mechanics principles, material properties, operating history, operational environment, in-service degradation, possible failure mechanisms, initial and final defect sizes, and usage of future operating and maintenance procedures to determine maximum tolerable sizes for imperfections."

Although these fracture mechanics methodologies are not commonly used in the pipeline industry, SI has been using fracture mechanics models routinely in the power generation industry for decades. These advanced methods, when properly applied, can enhance the reliability and safety of gas transmission pipeline infrastructure.

Footnote

[1] Select causes include manufacturing defects, fabrication or construction defects, or crack-like defect (such as SCC, seam defects, hard spots, or girth weld cracking)

Advanced Structural Analysis

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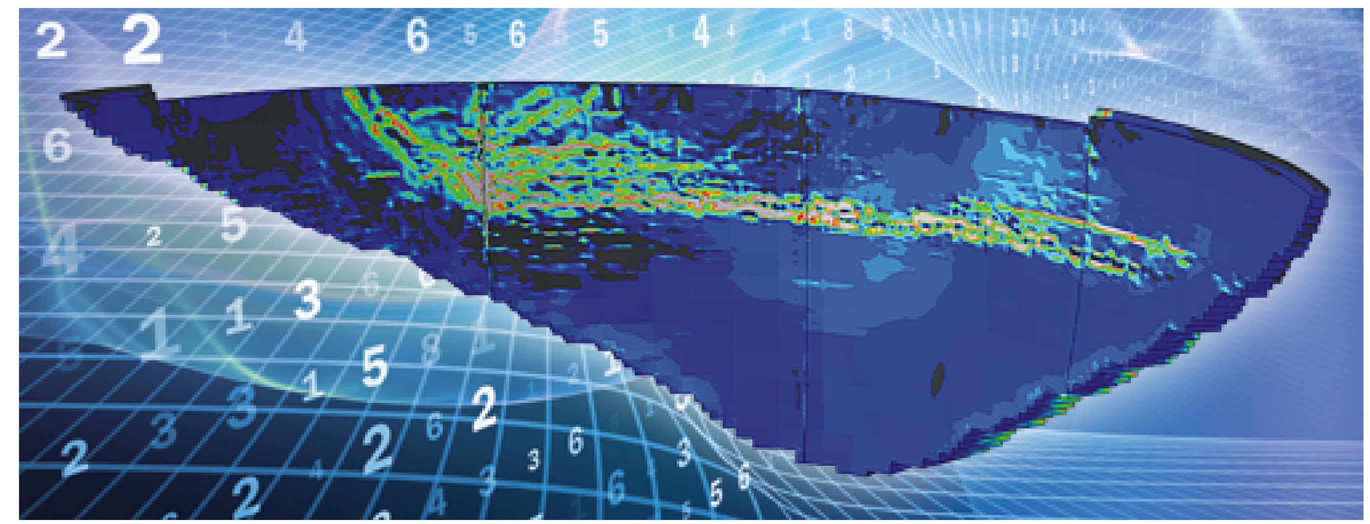
BELOW FIGURE 1. Reinforced Concrete Dam Cracking Results from an Abaqus Seismic Time-History Analysis Using the ANACAP Concrete Model



The sophistication of structural analysis has evolved side-by-side with computing and graphics technology. Structural engineers have at their fingertips very powerful software analysis tools that assist them in evaluating very large and complex structures for stability, suitability, and code adequacy. The tools themselves vary in complexity in proportion with the engineering analysis required of them - the most complex and unique engineering problems requiring the most advanced analysis tools. Structural Integrity is a leader in advanced structural analysis (ASA), utilizing state-of-the-art software and material science expertise to solve an array of structural and mechanical problems.

Structural analysis, in its most basic definition, is the prediction of the structural performance of a given structure, system, or component to prescribed loads, displacements, and changes in temperature. Common performance characteristics include material stresses, strains, forces, moments, displacements and support reactions. The results from a structural analysis are typically compared to acceptable values found in design codes. Meeting the design code acceptance criteria ensures a design that protects the public's health, safety, and welfare.

ASA extends this basic definition of structural analysis to one-of-a-kind problems where the acceptance criteria may not be well defined. Since loads, material behavior, or the structure itself can go beyond the scope of basic design codes, ASA requires an in-depth understanding of modeling techniques, software limitations, and non-linear material behavior. In ASA, sophisticated finite element analysis solvers are utilized to gain a detailed understanding of a system's non-linear mechanical behavior, providing a full three-dimensional view of the critical stresses and strains in a loaded system.

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Finite Element Solvers

Finite element modeling starts with the development of a finite element mesh to represent the structure under consideration. Boundary conditions, material properties, mechanical and thermal loads are then assigned to the model. The finite element solver then uses either an implicit or explicit method to determine the structure's response to the model definitions.

Implicit methods solve a finite element model by inverting the model's stiffness matrix. The time it takes to perform an implicit analysis is partly dependent on the size of the stiffness matrix and how many matrix inversions are required. Setting up the difference between implicit and explicit FEA program solvers and implicit solvers are impractical for non-linear problems.

For each time step, a linear analysis requires one matrix inversion while a non-linear analysis will require several matrix inversions to converge to a result. Implicit analysis can be used to analyze static loads or low frequency dynamic loading such as earthquakes. Implicit solvers are found in most structural analysis software including RISA, SAP2000, Abaqus, and ANSYS.

Implicit methods become problematic for highly non-linear problems. For these types of problems an explicit solver, which solves for nodal accelerations directly, is typically used. This allows a solution to be reached without the formation and inversion of a model's stiffness matrix (a computational savings), but the methodology itself requires significantly smaller (and hence more) time steps to reach a solution (a computational expense). Explicit solvers can be found in specialized structural analysis software including Abaqus Explicit and LS-DYNA.

Structural engineers require extensive training to properly perform ASA and understand modeling, software, and solver limitations.

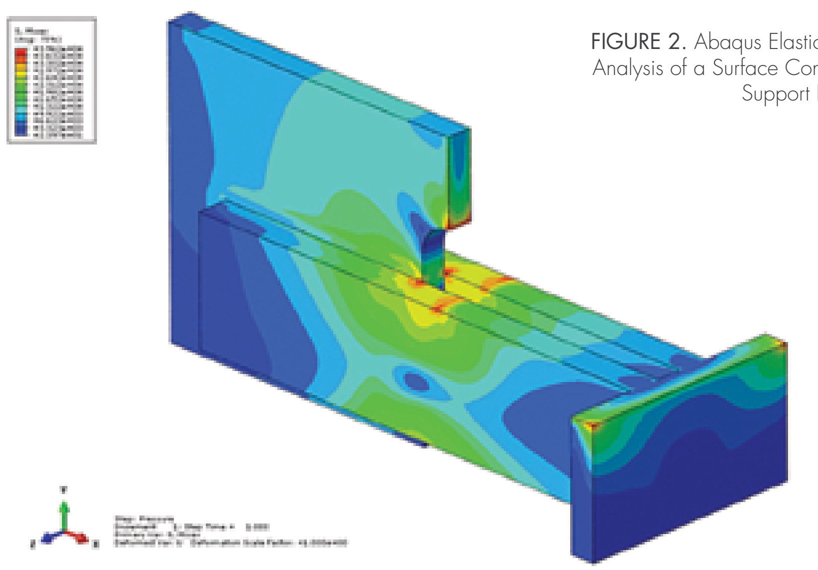
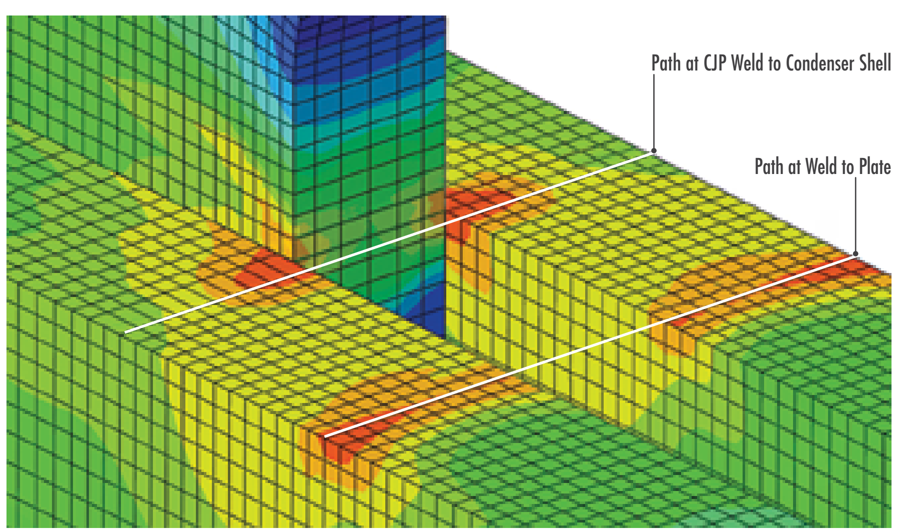


FIGURE 2. Abaqus Elastic-Plastic Analysis of a Surface Condenser Support Bracket



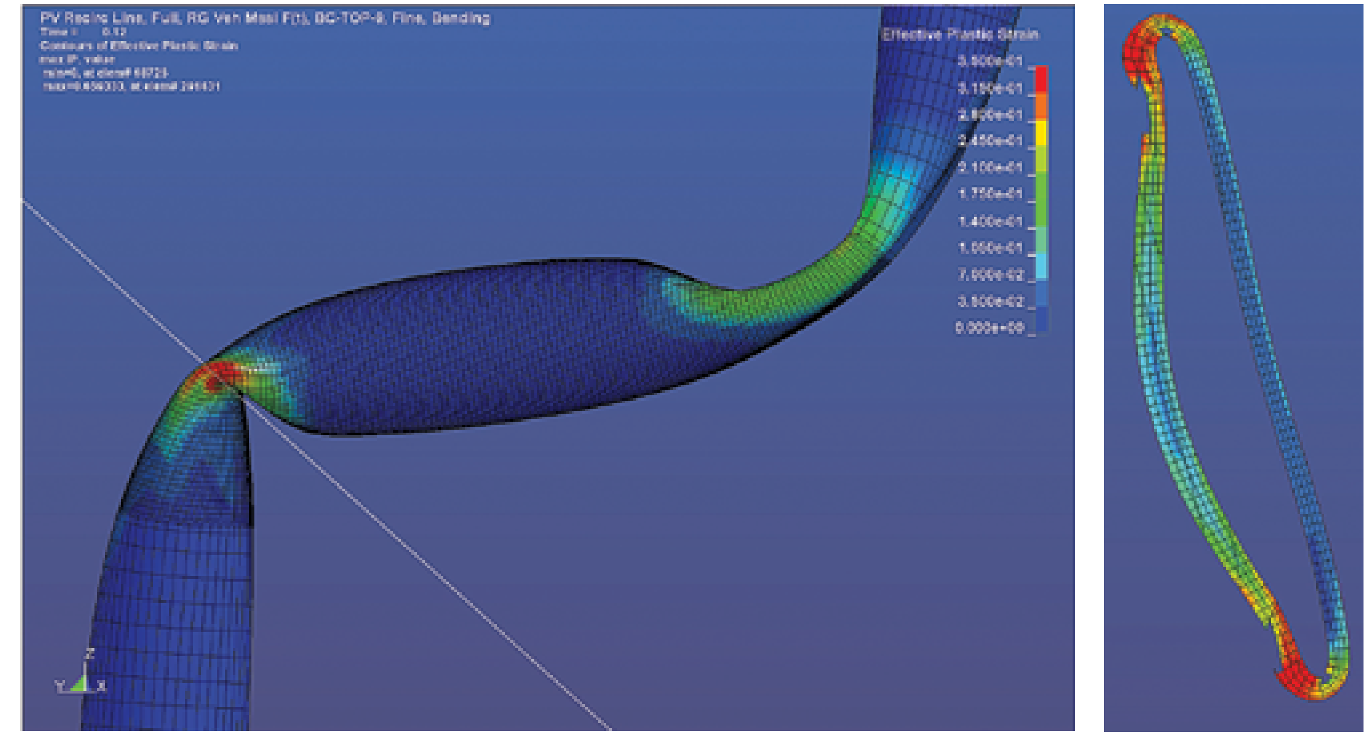
Advanced Structural Analysis of Concrete

Successful ASA of a concrete structure requires an advanced material model that captures the highly non-linear behavior of concrete and can converge to a solution involving severe material damage. Concrete material models that fail to capture degradation, account for triaxial stress states, load-rate effects, or time dependent material behavior can lead to erroneous results.

Structural Integrity's success in ASA of concrete structures stems from ANACAP, our proprietary concrete constitutive model. ANACAP has been shown to accurately represent concrete behavior in systems subjected to static, impact, and seismic loads and has been utilized in commercial, bridge, hydro, and nuclear power plant projects. The material model can account for cyclic degradation, multi-axial cracking, load-rate effects, aging, creep, shrinkage, compressive crushing, confinement, concrete-reinforcement interaction, and high-temperature softening. ANACAP can be utilized in all standard finite element shell or solid element formulations.

Figure 1 shows the extent of cracking in a reinforced concrete dam at the end of a non-linear seismic time history

BELOW FIGURE 3. LS-DYNA Simulation of Tornado Missile Impact on Ventilation Pipe and Resulting Restriction in the Cross Section



analysis utilizing the ANACAP concrete model. Within the ANACAP model, concrete cracks never heal once formed. This results in localized load redistribution, a better representation of the dynamic behavior of the model, and more accurate results when compared to "built-in" concrete constitutive models found in standard finite element libraries.

Advanced Structural Analysis of Steel

ASA of steel components typically includes coupled nonlinear thermal-mechanical analysis to assess the structural performance of new designs, as-built vulnerabilities, efficacy of retrofit modifications, or to perform root cause failure analysis. Structural Integrity commonly performs analyses to evaluate fatigue and fracture risks in steel structures where finite element modeling is often employed. When a system is comprised of several non-monolithic components, additional constraints are included in the finite element model to accurately represent the contact and interaction that might occur between the components during the analysis sequence.

Figure 2 shows localized stress results from a non-linear analysis of a steel condenser support bracket. The model was used to determine the original design's cause of failure and to develop a retrofit strategy. The model accounted for high operating temperatures that have a non-linear impact to the mechanical properties of the steel components. 3D brick finite elements were used in a fine mesh to model the configuration of the welds and to simulate the structural load paths accurately. Output from this analysis was utilized in fracture mechanics calculations to predict the service life of the bracket when subject to low frequency cyclic loading.

Shock, Blast, and Impact Structural Analysis

Explicit finite element solvers are typically required to evaluate shock, blast, and impact problems when traditional calculation methods lead to unrealistic or overly conservative results. The ASA of complex loading scenarios such as tornado missile impact, aircraft impact, load drop, or bomb blasts is a specialty of Structural Integrity, especially when applied to critical infrastructure (e.g., nuclear facilities and other safety-related structures).

Figure 3 depicts plastic strain contours from a tornado missile impact analysis of a safety-related ventilation duct. Since the duct is required to remain functional after impact, an accurate estimate of the duct's post-impact deformation was needed. The restricted cross section of the plastically deformed model was measured and used to determine if the duct's ability to function remained above a minimum acceptable threshold.

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Soil-Structure Interaction and Seismic Analysis

Large critical structures, facilities, and equipment that are exposed to earthquake excitation often require ASA to account for the interaction between the structure itself and the underlying soil. Improved structural response estimates are obtained when this soil-structure coupling is accounted for. Soil-structure interaction (SSI) problems have been historically solved with SHAKE/SASSI, spectral analysis software, although programs such as LS-DYNA are now offering similar analysis capabilities. Expertise in soil mechanics and foundation engineering is a prerequisite for proper SSI analysis.

Seismic analysis, with or without SSI, is performed to determine a structure's response to ground motions. Different seismic analyses have different degrees of complexity and might include equivalent force analysis, response spectra analysis, non-linear pushover analysis, or non-linear time history analysis. The structure's response to a seismic event is used to ensure sufficient structural capacity and may also be used as input in fragility analyses of housed systems.

Facilities often house critical equipment that needs to be operational following a seismic event. The criteria to determine the equipment's functionality might be stress- or strain-based for mechanical components, but is often acceleration based, especially for electrical components. Fragility analysis compares the local accelerations, imposed by a seismically loaded structure on the housed equipment, to the acceleration limits that the equipment can withstand and still function (as substantiated by testing or analysis). These analyses are often performed for nuclear facilities where both the structure and internal equipment need to remain functional following a seismic event. Figure 4 shows an ANSYS model and a modal response of an emergency cooling tower subject to a beyond design basis seismic event (BDSE), which was used in a fragility evaluation. The finite element analysis and subsequent calculations served to demonstrate the cooling tower's resilience and ability to remain functional after BDSE.

Conclusion

There are many other examples of ASA that cannot be adequately covered in this brief. Some of these include fluid-structure-interaction problems, or the evaluation of reciprocating equipment or pressure vessels. The necessity of ASA is dictated by the nature of the loading, the complexity of the problem, and the importance of the analyzed component. The proper execution of an ASA requires trained experts who often utilize sophisticated software tools to facilitate the analysis. Structural Integrity specializes in ASA and has significant depth in technical resources, making it a leader in ASA.

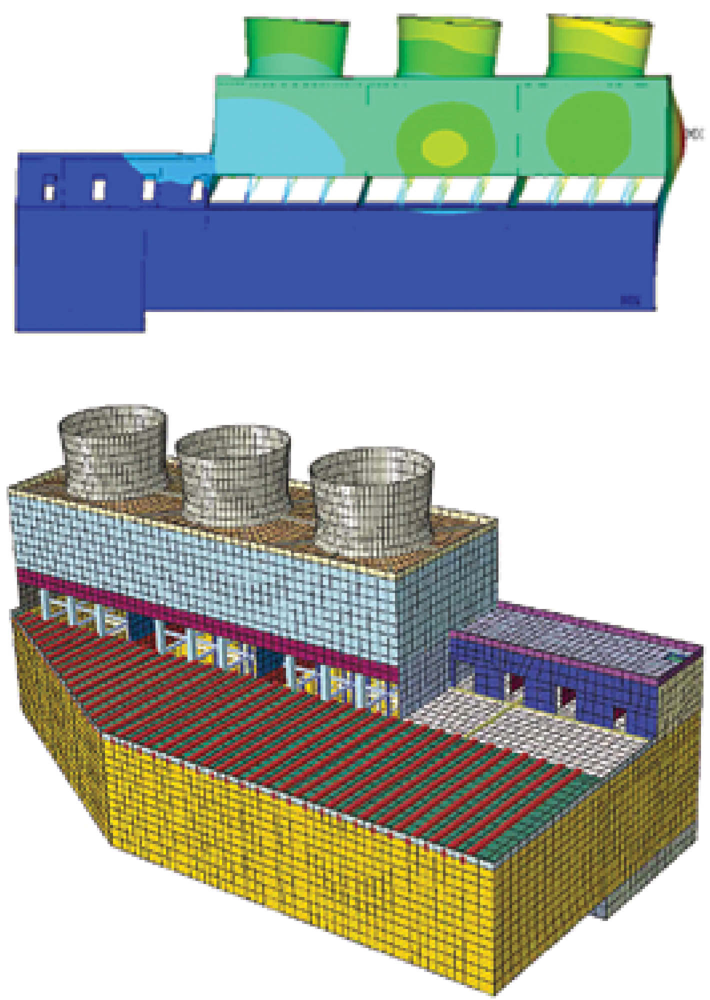
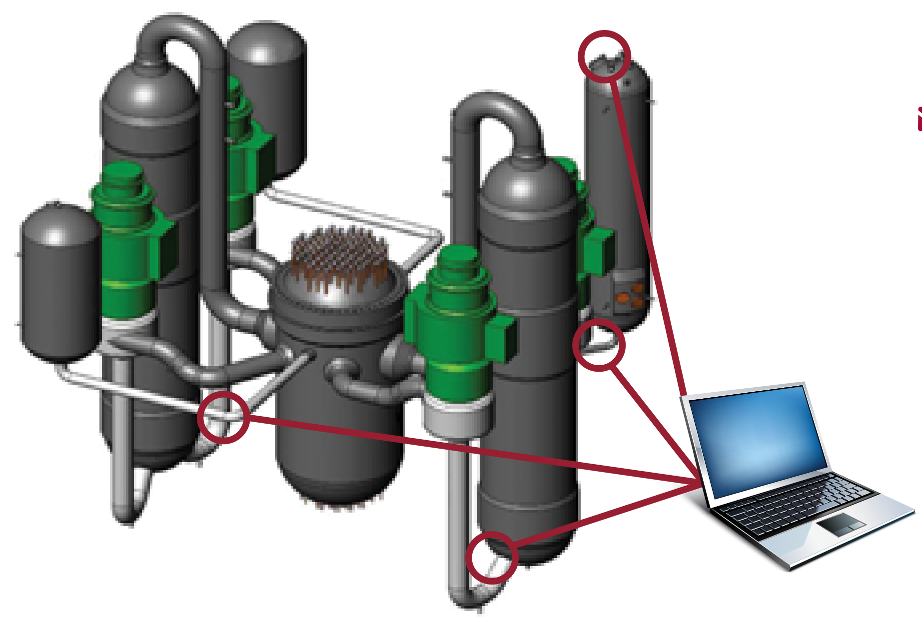


FIGURE 4. ANSYS Finite Element Analysis of an Emergency Cooling Tower Subject to a Beyond Design Basis Seismic Event

Managing Fatigue-Challenged Components in SLR



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Subsequent License Renewal (SLR) will require a shift in the approach for managing plant components for thermal fatigue. The components are older and will have experienced more fatigue damage. As time goes on, more components will become fatigue-challenged, meaning that they will require more management to demonstrate serviceability.

There are several approaches that can be taken to manage fatigue-challenged components in SLR.

Refining the design fatigue analyses is one approach that has been widely used in License Renewal (LR), and will remain useful in SLR. Components that were previously managed through cycle counting alone may still be managed through cycle counting if a refined analysis results in fatigue and environmentally-assisted fatigue (EAF) cumulative fatigue usage values below 1.0.

Another useful approach is to revisit assumptions made about plant operation earlier in life. Conservative assumptions were made about early plant operation for many components. This was often done for expediency and may have been sufficient for LR, but as the components age, those assumptions may prove too conservative. Revisiting these assumptions can help lower the overall fatigue usage for components.

Fatigue monitoring is another approach that has been widely used for LR and will prove even more useful in SLR. As more components become fatigue-challenged, expanded monitoring will be important. For those components already monitored, converting to more refined monitoring methods can help remove excess conservatism and lower the overall fatigue usage.

When it becomes impossible to demonstrate that the fatigue or EAF usage for a component will remain below 1.0, component inspection and flaw tolerance is the next step to demonstrate serviceability. When an inspection is performed and no flaws are identified, ASME Code Section XI, non-mandatory Appendix L contains guidance for performing a flaw tolerance evaluation to accompany the inspection. The Appendix L evaluation sets the inspection interval by calculating the allowable flaw size and crack growth rate of a postulated flaw in the component.

SI:FatiguePro 4.0 (FP4) contains a Fatigue Crack Growth (FCG) module to support the inspection and flaw tolerance approach. The FCG module uses either plant data or simulated design transient data to calculate crack growth for a real or postulated crack. It can be used both to perform the Appendix L evaluation to determine the inspection interval and to monitor crack growth over time to confirm the Appendix L results. If the inspection interval is less than 10 years, the confirmatory monitoring may even be used as a basis for increasing the inspection interval.

Wind Project Continued Operation

Beyond Designed Life

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With the increase of renewable energy into the power generation market, aggressive state renewable targets, and recently renewed production tax credit (PTC), wind power generation demand is positioned to increase significantly. This is good news not only for new wind projects but also for existing wind power infrastructure.

As the wind energy market and demand has grown quickly, so has the technology - better turbine controls, more efficient drivetrains, longer and lighter blade designs, and taller towers. Figure 1 shows that in 2000 wind turbines had an average nameplate capacity of slightly less then 1 MW and 30% capacity factors, while the average nameplate capacity in 2016 was 2.15 MW [1], with capacity factors near 40%. Blade lengths of 25 meters in 2000 are dwarfed by the more recent 50 meter blades (see Figure 2). Longer blades at higher hub heights and more efficient controls means that new wind projects can achieve more power generation capacity with half (or less) the number of turbines compared to 10-year-old projects.

A typical wind turbine is designed for 20-year operation. In 2017, most of the US wind turbine fleet is less than 10 years old, with 20% of the fleet between 10 and 16 years of age. As wind turbines age and near their design life of 20 years, owners should start assessing their future options for continued operation:

1. Partial repowering: Would it be beneficial to invest in upgrades that take advantage of new technology to increase power generation and/or turbine life?
2. Repowering: Given technology development, is it better to replace existing wind turbines with new ones?
3. Life extension: Can the operating wind turbines continue operating past 20 years as-is (or with minor adjustments)?

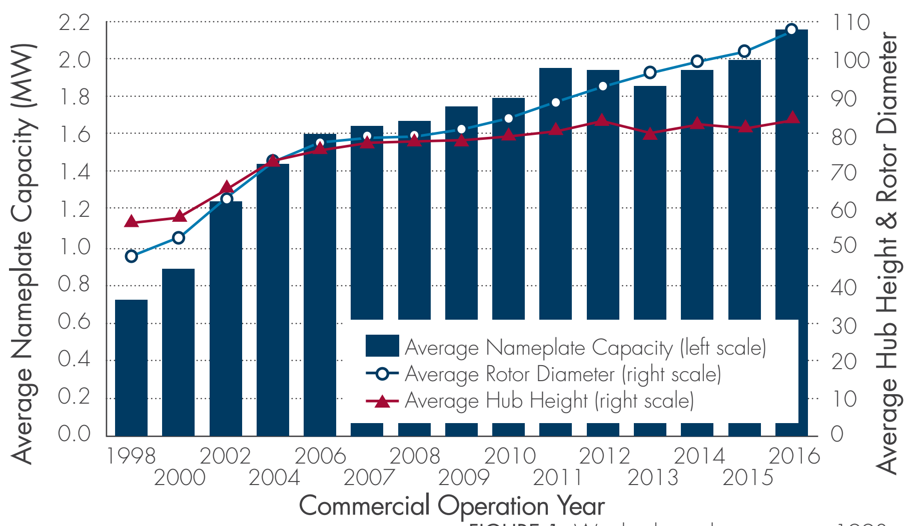

FIGURE 1. Wind turbine changes since 1998.
Source: Lawrence Berkley National Laboratory [2][3]

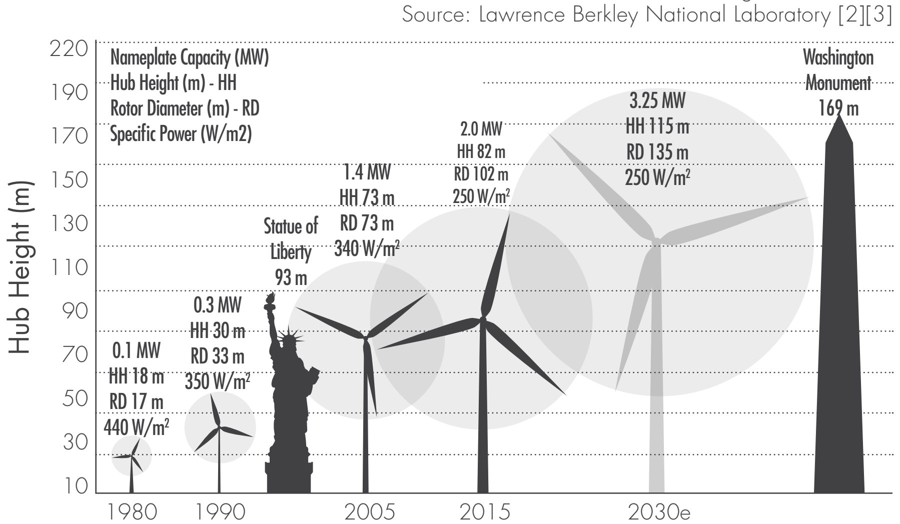

FIGURE 2. Wind turbine advancements and growth forecast.
Source: Lawrence Berkeley National Laboratory [2][3]

The answers to these questions are project and site specific.

For existing projects, the recent PTC stated that a 10-year extension could be applicable if 80% of the turbine's value is replaced by upgrades. This has led many owners/operators to consider partial repowering of their fleet. Partial repowering a wind turbine entails replacing up-tower components and equipment but keeping the existing foundation and tower intact. Partial repowering a 15-20 year old site would seem beneficial since permitting, grid connection and infrastructure is already in place. But the reality is that in many cases the existing balance of plant, foundation and tower will significantly limit the type of upgrades to the point that only a small increase in energy production will be achieved. This small increase in Annual Energy Production (AEP) will not offset the capital expenditures required to upgrade. Figure 3 shows various upgrades available aftermarket with typical energy gains [4].

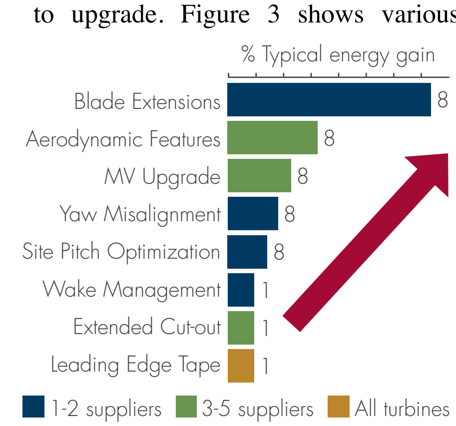

FIGURE 3. Energy gain from aftermarket upgrades. Source: MAKE [4]

Re-powering (full) involves the same site but with full replacement of old turbines with state-of-the-art turbines with more generation capacity. At first glance, this option would seem like starting a new project, which in many aspects it is. But it has some advantages over starting a new greenfield site. The re-powered site has existing infrastructure such as access roads, grid connection, personnel, and the site conditions are well known which can save site permitting and wind assessment hurdles. A National Renewable Energy Laboratory (NREL) economic study[5] on repowering suggested that repowering becomes more attractive relative to investing in a new site for projects after 20-25 years of operation. The goal of repowering is to increase power generation capacity that involves a substantial capital expense. The decision to repower lies mainly in the financial balance; on one side is the repowering return on investment, and on the other is the current project's operations and maintenance (O&M) costs.

Another option is the continued operation of the wind turbines past their 20-year mark with minimal capital expenditure. Wind turbine life extension guidelines and standards are available not just for wind turbines (DNV-GL or UL) but for many other machinery applications (ISO 13822). For wind turbine life extension the owner needs to review actual wind loading conditions to-date and how that compares with initial/design life estimates, assess the current condition of the turbines, then estimate the remaining useful life of the wind turbines, and then develop an appropriate O&M program for continued operation.

The process of evaluating the various options described above for continued

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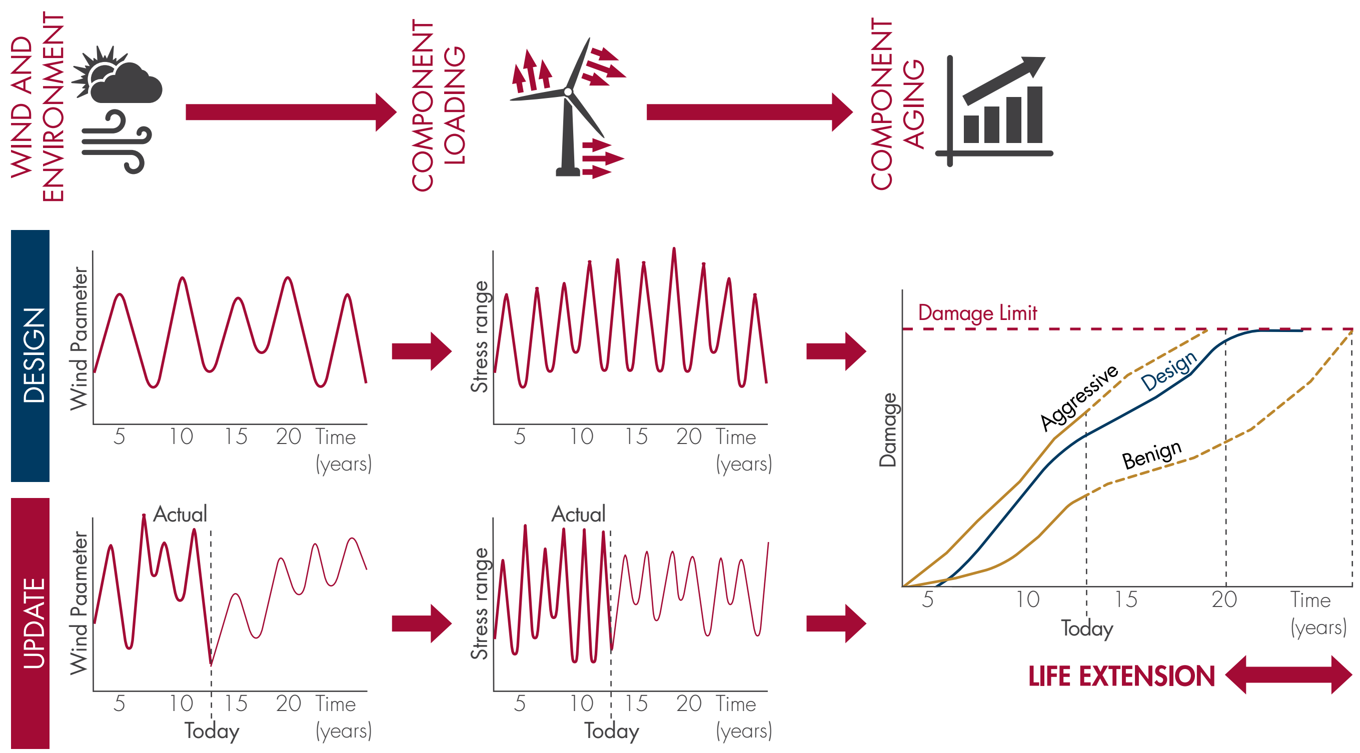

FIGURE 4. Wind turbine lifetime estimates; design, update (actual) and extension beyond 20 years.

operation depends on three different but related stages of wind turbine/component lifetime estimation. Figure 4 depicts the steps for different stages of wind turbine lifetime estimation, design life estimates, lifetime update, and lifetime extension.

Wind Turbine Design Life Estimates

Wind turbine designs following the International Electrical Commission (IEC) and DNV-GL design guidelines are based on specific IEC wind classification, with a total of four different wind classes. Each wind class assumes a nominal operating wind speed and certain frequency of extreme events. Table 1 is an extract from the IEC 64100-1 standard. Class I is considered high wind speeds and class III slow wind speed regimes. Wind turbine OEMs use these wind classes to design different turbine models and generally have several options for various wind speed ranges and hub heights. For lifetime (or fatigue) design, the IEC 64100-1 provides a general distribution for different scenarios. The technological trend has seen more offerings as modular turbine components can be mixed and matched to the specific site conditions[4]. The final decision to purchase and install specific turbines/components falls on the project development team based on wind availability forecasts, component and turbine characteristics, and OEM contracts.

While wind availability forecast is a major driver for project feasibility, site assessment ultimately defines turbine life. During project development, wind availability forecasting is made by gathering met mast data and meteorological simulations, and extrapolating a trend from that data. For projects older than 15 years, the wind resource and site assessment process was not as developed as it is now, resulting in wind regime and wind loading histories with high uncertainties. With an "expected" wind loading and operation, site-specific design assessment for 20-year fatigue life can be performed for prospective wind turbines in the market.

Wind Turbine Life Update

After years of operation with local measurements such as local met masts, SCADA data, anemometer data, maintenance reports and/or condition monitoring systems (CMS), the fatigue life of the turbine can be updated. Figure 4 shows two possible scenarios that differ from the as-designed scenario. An aggressive scenario such that wind loading, operation and environmental conditions were underestimated during development that could result in shorter than 20 year life-span; or the opposite where the wind loading and operation have been benign and the turbine is expected to survive past 20 years. For the aggressive scenario, where O&M expenses might start to impact the profitability of the project, it may be beneficial to consider repowering (either partial or full). For the benign scenario, the question now turns to how much longer can the turbines run safely and what will be the ongoing O&M program costs.

Wind Turbine Class		I	II	III	S
V_{ref}	(m/s)	50	42.5	37.5	Values specified by the designer
A	I_{ref} (-)		0.16		
B	I_{ref} (-)		0.14		
C	I_{ref} (-)		0.12		

TABLE 1. Basic parameter for wind turbine classes [1]

In Table 1. the parameter values apply at hub height and
V_{ref} is the reference wind speed average over 10 min
A designates the category for higher turbulence characteristics
B designates the category for medium turbulence characteristics
A designates the category for lower turbulence characteristics and
I_{ref} is the expected value of the turbulence intensity[2] at 15 m/s.

Wind Turbine Life Extension

With accurate and current data gathered, a turbine and component risk prioritization/evaluation can be performed so that a risk based inspection program can be developed. Analytical estimates are based on models that have certain assumptions and uncertainties. Performing inspections for the higher risk (and/or high uncertainty) components could help reduce model uncertainty, and provide more accurate and current damage or degradation states. These inspections would span all components (but not all turbines in a project, nor all components within one turbine) and would include visual inspections (using drones for example), targeted non-destructive inspections (such as ultrasonic phased array, dye penetrant, thermography) and if necessary material testing (non-destructive if possible).

Following these inspections, any discovered degradation will serve as inputs to the damage propagation models, strength degradation models and fatigue analyses to get a remaining useful life for the component. There are two main methods for fatigue analysis; the fatigue cycle accumulation method which is typically used during design that does not depend on exact damage characteristics, and the damage propagation method that accounts for damage characteristics and local effects (within component/part) and loading. The fatigue cycle accumulation method is useful when the presence of damage is unknown. But if damage has been discovered, the advantage of the latter method is that it results in targeted re-inspection and/or repair scheduling, rather than pre-defined interval inspections, which would minimize maintenance costs.

The process of risk-based inspections plus remaining useful life assessments would build the wind project's structural lifecycle asset integrity management program. Such a program incorporates condition-based maintenance that provides early warning of potential failure or future systematic failures and helps the optimization of resource allocation planning[6], allowing the project's continued operation beyond the 20-year mark.

Continued operation evaluations are not unique to the wind power industry. Nuclear, coal, natural gas and combined cycle plants have gone through similar evaluations and re-certifications. Many of these plants, have seen a transition from running at base load to more frequent start/stops (due to the integration of renewables), which is a considerable change from their design basis. For nuclear plants, the Nuclear Regulatory Commission (NRC) license renewal requires the analysis of aging components and for operators to establish suitable aging management programs. At Structural Integrity we have developed the expertise and tools to help our clients with component and system lifetime assessments, and to support the implementation of optimum maintenance programs for their safe continued operation.

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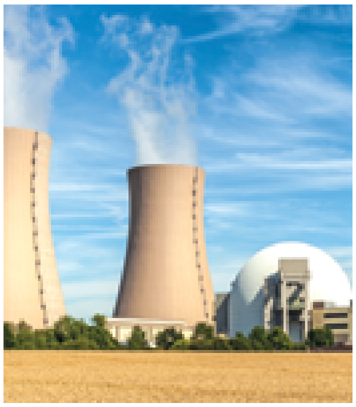

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UPCOMING EVENTS

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ISPE Conference – San Diego, CA – October 29 – November 1, 2017 *Exhibiting*

ANS Winter Meeting – Washington, D.C. – October 29 – November 2, 2017 *Attending*

ASCE 43 Committee Meeting – Las Vegas, NV – November 2-3, 2017 *Hosting*

EQ Technical Meeting – Clearwater Beach, FL – November 8-10, 2017 *Exhibiting*

OCNI Bruce Power Supplier's Day – Canada – November 11, 2017 *Exhibiting*

Power Gen – Las Vegas, NV – December 5-7, 2017 *Attending*

Bismarck EnergyGen – Bismarck, ND – January 23-25, 2018 *Exhibiting*

Annaul ASHRAE – Chicago, IL – January 20–24, 2018 (Critical Structures & Facilities) - *Attending*

HRSG Forum with Bob Anderson – Houston, TX – March 5-7, 2018 *Exhibiting*

NRC RIC 2018 – Washington, DC – March 13-15, 2018 *Attending*