



# Inspectioneering Journal

ASSET INTEGRITY INTELLIGENCE

FEATURED ARTICLE

## HIGH-ENERGY PIPING SYSTEMS: AVOID CRACKING UNDER PRESSURE

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**VOLUME 21, ISSUE 1**

JANUARY | FEBRUARY 2015

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**Editors Note:** Although this article comes from the powergen industry, the issues with piping integrity and challenges we face in the oil and gas and petrochemical industries are similar. Hence, we share this article with the IJ readership hoping that you will find the article of value. Benchmarking against similar but different industries is a healthy practice and encouraged to break out of our traditional ways of thinking and to see how others are addressing similar challenges. We are confident that many of the challenges addressed in this article will resonate with you.

Avoiding cracking under pressure when managing high-energy piping systems is common subject matter in the power industry. Just as high-energy piping can give way to pressure, stress and fatigue, so can the people in charge of operating them when trying to determine what to inspect, where to inspect, and what to do with those inspection results once they have them.

We have all heard the term, “*the squeaky wheel gets the grease.*” In the case of power plants that squeaky wheel tends to be boiler tube failures. Unfortunately, piping is quiet, until it isn’t. In most cases, I personally enjoy surprises; however, when it comes to safety, surprises are NOT welcome. It goes without saying that high-energy piping systems are essential to the safe and cost-effective operation of power plants. Unfortunately, the likelihood for piping failures increases with the age of the systems involved. The question isn’t if piping systems will fail, the question is WHEN they will fail.

Prolonged operation, particularly at elevated temperatures, results in metallurgical degradation. This in-turn increases the potential for cracking and crack propagation until a final failure stage is reached by the component. As a result, power plant operators have become increasingly cognizant of the importance of condition assessment evaluations for high-energy piping systems.

The difficult task of managing the safety and integrity of these systems becomes even more complicated when many piping managers are faced with specific challenges that have become a trend in the power industry. These challenges include the reduction of onsite engineers, aging workforces, aging equipment, and the need to remain competitive in a challenging global energy market. Piping managers are routinely faced with the complex task of evaluating the current condition of their equipment, forecasting outage budgets and schedules, and performing risk assessments. Additionally, insurance companies are increasingly requiring inspection and maintenance records that often times are not up-to-date or readily available. This notion was recently reinforced when I attended a conference where James Chiles, author of *Inviting Disaster*, stated an interesting and relevant fact of the power industry: “over half of the senior staff will be retiring by 2020. Knowledge capture that provides information that is usable and readily available is paramount.”

The solution to safely maintaining the integrity of high-energy piping systems involves taking a comprehensive approach to

piping management utilizing unit specific operational training, advanced data capture and management, and strategic inspection, maintenance, and replacement prioritization. Implementing this comprehensive approach has resulted in avoiding both catastrophic and leak type failures for plant managers. Utilizing a unit specific, targeted plan enables utility owners and operators to succeed in today’s competitive market by increasing the unit’s reliability and availability without sacrificing safety or environmental standards.

## AVOID CRACKING UNDER PRESSURE: UNIT SPECIFIC STRATEGY

Each facility has its own unique operational history and conditions. In order to prolong the integrity and ensure the safety of your critical piping systems, it is imperative to consider your facility’s unique conditions to develop a strategic plan. Because of the overwhelming nature of the task, many plant managers and engineers never get started with an integrity program. Luckily there is technology available on the market that can help; powerful data management programs that can better enable utility personnel to access, review and manage all previous inspections, repairs and recommendations associated with any area of their critical systems. Features like 3-D visualization of the components allows for easier understanding of existing damage mechanism locations and enables tracking these mechanisms with the click of a mouse. This technology, paired with sound root cause analysis and failure prevention strategies, provides a method of developing an effective approach for improving reliability and risk management. Thielsch’s 4-SYTE System Strategy Program utilizes a 3-step approach to developing a unit specific strategy, which has resulted in avoiding both catastrophic and leak type failures in power facilities across the nation. The 3-step approach includes a system review, a historical review, and a budgetary review of each unit. Several of the considerations involved in each review process are discussed in this article.

### STEP 1 - System Review

#### Age of the Unit

Facilities built in the 1960s and 70s experience damage related to the obvious number of hours of operation, however they were designed with heavier wall thickness. As a result, these units tend to have longer life expectancies than some of the newer facilities. Facilities that were built in the 1980s pushed the limits with the “do more with less” approach. Piping was supplied with thinner walled spool pieces, conserving costs on construction, but

ultimately reducing the service life of the critical components. Modern facilities are being constructed to adapt to the thermal cycling that has become a part of the energy culture of today and are experiencing earlier than expected failures. Many of these failures are the result of exotic materials that are being used which have not been in service long enough in the industry to know the true historical behavior of the material under the thermal and mechanical stresses of cycling a unit.

### Design of the Unit

During the operation of a modern steam turbine, moisture in the turbine will cause erosion on the turbine blade. This results in high maintenance costs and loss of power production and thus a loss of revenues that usually is far greater than the maintenance costs. Therefore, all modern fossil power plants use superheated steam, which is conveyed through the “Main Steam Piping” system, and many of the large utility plants use a second superheater (called a reheater) that reheats the steam after it has passed through a portion of the turbine. This is usually done on a utility boiler application after the initial superheated steam passes through the high-pressure section of a turbine. The lower-pressure steam from this section of the turbine returns to the boiler, where the steam temperature is increased, and then returns to the turbine through the “Hot Reheat Piping” system.

Another operating system widely utilized in the industry today is the combined cycle heat recovery steam generator (HRSG). HRSGs are typically classified into one of two types defined by the orientation of the exhaust gas flow: horizontal or vertical. Most HRSGs in North America are horizontal arrangements which feature natural circulation, typically consisting of multi-pressure steam systems: high-pressure (HP), intermediate-pressure (IP), and low-pressure (LP). Smaller units, such as peaking plants, may have a dual pressure system. Larger, triple pressure units often add a reheat system to further boost the overall cycle’s thermal efficiency. These new breeds of HRSGs were designed to operate at substantially higher flue-gas temperatures and steam pressures utilizing advanced, and for the most part, untested, boiler steels. The end result of these advances have yielded higher combined cycle efficiencies, however they have also created higher thermal stresses, fatigue cracking, creep damage, and corrosion concerns, particularly as units designed for base load were forced into cycling duty. These problems can manifest themselves within a few short years of commissioning and cause expensive and time consuming repairs.

Prior to determining the prioritization of inspection of a high-energy piping system, every effort should be made to assemble all applicable information on that piping system.

This would include, but not necessarily be limited to:

- Design Code
- Design pressure and temperature
- Operating pressure and temperature
- Operating hours
- Operating mode, e.g., base-loaded or cyclic
- Number of unit starts and characterization of start type
- Number of operating hours at off-design conditions

- Any upset operating conditions that could affect piping system integrity (This could include safety valve operation, turbine trips, water hammer, etc.)
- Pipe spool drawings
- Isometric drawings
- As-built drawings
- Fitting drawings
- Weld detail drawings
- Hanger support detail drawings (If this data is not available, then field hanger support audits are necessary)
- Valve weights
- Original pipe stress analysis required for design acceptance (If this is not available, then turbine nozzle loads and boiler connections loads are necessary)

### Materials

The American Society of Mechanical Engineers (ASME) has approved certain steel materials for use as tubes in boilers designed according to the ASME Boiler and Pressure Vessel (B&PV) Code. Section I of the ASME B&PV Code specifies allowable materials in Paragraph PG-9.

Understanding the materials specific to a unit and recognizing the inherent concerns of those materials (weldability, resistance to elevated temperatures and pressure, heat transfer ability) will enable facilities to be more progressive in their pursuit to preventing service related damage.

### Hanger Supports

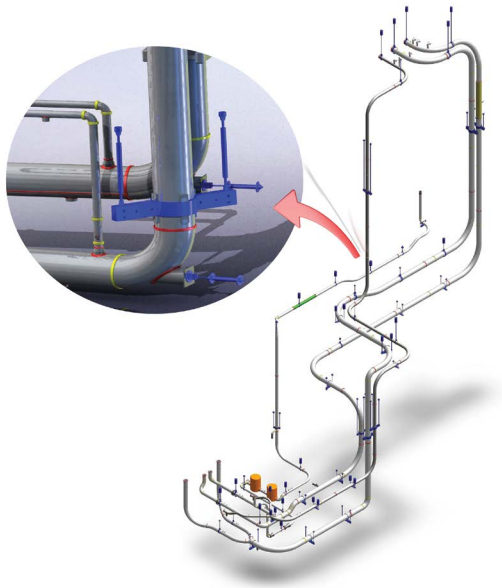
Hot and Cold condition walkdowns of the hanger supports in each system should be audited annually. This will ensure that the piping systems are supporting as predicted and intended by the designer (The condition of the supports provides an accurate barometer of the overall condition of the applicable high-energy piping system. This is supported by the fact that over 95% of the through wall failures reported in high-energy piping systems are related to applied bending stresses from external or off design conditions. Oftentimes these stresses are the result of improperly designed or malfunctioning hanger supports). **Figure 1** illustrates a typical hanger design and location.

Important factors to keep in mind when evaluating hanger supports:

- Design of expansion and contraction of the system as it heats up and cools down.
- Supports should be moving within the design range – not necessarily at the design settings (i.e. not topped out or bottomed out and moving in the correct direction).
- Annual support inspection walkdowns are a must.
- Load adjustments should only be made in the hot condition and only by qualified individuals.

### Understanding P91

The use of modified 9Cr (grade 91) steel in modern power plants



**Figure 1.** Typical hanger design location.

is derived from the superior properties of the material compared to carbon steels or lower chrome materials. It boasts superior creep and tensile strength characteristics, which allows for thinner materials to be designed into piping systems, pressure vessels and tubing. These are enviable characteristics in terms of thermal cycling, hence the wide spread use of the material in newer combined cycle plants.

There are some critical drawbacks to this material that have been realized over its relatively short lifetime. It provides significant field welding challenges in terms of backing, preheat, and post weld, heat treat programs. There is little margin for error when welding and/or heat treating this material. Unlike carbon and low-alloy steels, the elevated creep strength in 9-Cr material depends on achieving and maintaining a specific microstructure.

Any event during manufacture, erection, or operation that disrupts this microstructure will compromise the integrity of the material and prevent it from achieving the creep properties upon which the Code's allowable stresses are based. In such cases, the premature failure of such components is a reality. Additionally, softening of the material results in lower creep strength and can initiate type IV cracking of the material. It is paramount that the use of this material be firmly understood.

## STEP 2 - Historical Review

### Failure/Damage Locations

The ability to identify and track the locations of a piping damage or failure and its root cause is essential to comprehensively maintaining the safety and integrity of the high-energy piping systems. Once the root cause of the failure/damage is properly identified, a long term plan can be implemented to ensure the failures/indications have been rectified. Proper and current documentation is critical to managing failures and indications, and can be done in real-time with the use of an effective data management program.

### Failure/Damage Mechanisms

Although numerous conditions may cause or lead to service failures, the responsibility for a failure can generally be assigned to one of five classifications:

- **Design:** structural, design notches, joint location, or welding end configuration
- **Materials:** selection and handling of base and welding materials
- **Base Metal Defects:** introduced during manufacture and shaping of plate or piping components- pipe, cast valve, cast or forged fitting, etc.
- **Fabrication:** fabrication, welding, heat treatment, or cleaning of pressure vessels or piping during shop fabrication or field erection
- **In Service:** fatigue, creep, thermal shocking, corrosion, and overload

In some instances, the responsibility can be related to a combination of these classifications. For example, a pipe weld containing root defects, such as lack of penetration, may not fail during service until thermal or mechanical fatigue of sufficient magnitude initiates cracking and crack propagation of the existing defect through the cross sectional thickness occurs. **Figure 2** illustrates a typical surface indication, which required repair welding. The indication was discovered during a routine scheduled outage inspection.

A failure occurs by cracking or corrosion or sometimes a combination of both. The majority of failures occur gradually, in a ductile manner. They involve either a gradual propagation of cracks or corrosion across the wall thickness of a component. By bulging or leaking, ductile failures give warning to the operating personnel. It is fairly rare to experience a failure where partial cracking across the wall occurs, followed by a sudden pipe rupture, or where sudden rupture occurs which is not preceded by detectable prior cracking. These sudden rupture type failures are viewed with extreme concern as they may result in injury of personnel or loss of life, and many become extremely costly to the plant. Most of these failures are related to the brittle behavior of certain materials. Three conditions control this tendency for steel to fail in a brittle fashion. These include: (1) high stress concentrations; (2) a high rate of straining; and (3) environmental temperature. Although brittle failures are often considered the most catastrophic, it is important to recognize that cracking through ductile metal may also have considerable consequences.

### Modifications

On occasion, inherent deficiencies of a unit design will be identified. As a result, the unit may undergo design modifications which can resolve the original design flaw concerns, but ultimately can create other issues such as steam flow restrictions and temperature excursions etc. Additionally, as part of the clean air initiatives currently underway, many units are being modified to burn alternative fuels. Recognizing what modifications have transpired in a specific unit should be considered for potential side effects which may be occurring as a result of those modifications.



**Figure 2.** Example of a surface incitations discovered during a routine outage inspection.

### Replacements

As an aging plant begins to experience repeated failures, sections of piping will require replacement. These replaced sections will have fewer hours of operation; therefore, they often will not need to be considered for inspection on the same schedule as original equipment within the unit. This observation is particularly unit specific and is a major basis for why a cookie-cutter approach to inspection/maintenance is ineffective and can lead to squandering precious budget funding inspecting equipment that has not yet reached a point in its life cycle to require examination.

### Operational Changes

Most power generation facilities were designed on the assumption that they would be operated in a base-load mode or infrequently cycled. However, in response to local power market conditions and the terms of their power purchase agreements, many plants are now cycling their units more frequently than designers had intended. This results in greater thermal stresses, more pressure cycles, and therefore more cyclic fatigue damage and overall faster wear and degradation to the critical components due to both the mechanical and corrosion processes.

As a general comment, cycling service has an adverse effect on the life expectancy of a unit. This is due to the fact that cycling results in fatigue loading (alternating cyclic stresses), whereas base load operation results in creep (sustained stresses). Depending on the severity of the stresses and the number of cycles, fatigue loading can result in cracking, particularly at restraint locations.

### Upset Conditions

When a unit trips and is brought offline suddenly or experiences a water hammer event, an immense amount of thermal and mechanical fatigue can be introduced to the involved components. It is beneficial to understand if a unit has experienced any major upsets during its life cycle in order to determine if evaluating areas that wouldn't normally come under the microscope is necessary. This is similarly unit specific and would be

comparable to the considerations you would evaluate if you were purchasing a used car. Just as the purchaser would investigate any past maintenance troubles or collisions of the vehicle prior to purchasing, plant managers must consider the history of their units prior to determining the inspection prioritization of their critical components.

If a high-energy piping system has been subject to an upset operating condition with the potential to affect the integrity of that piping system, consideration should be given to performing an inspection of the piping system as soon as practical after the event to evaluate the effects of the event. The following provides examples of upset operating conditions that may require further investigation.

For high-energy piping systems exposed to fires, the inspection should include visual examination of the lagging in an effort to identify possible exposure temperatures. In those areas where the piping system was exposed to temperatures in excess of the melting temperature of the lagging and was exposed to fire suppression activities, consideration should be given to performing replication and hardness testing to identify changes in microstructure that could adversely affect the material performance and lead to premature failure. (Other nondestructive examinations may also be prudent.)

High-energy piping systems are subject to severe water hammer. The initial inspection after such an event should focus on the pipe supports in an effort to identify the actual movement of the piping system. This should be followed by nondestructive examination of the weldments in those areas that were subject to the greatest movement. If any event-related deterioration is identified, the scope of inspection should be expanded. Ultimately, this condition can be avoided by proper steam line draining programs and maintenance of the automatic drains. Frequently the collection of condensate in the lower horizontal sections of the Cold Reheat piping system as a result of steam condensing during unit shutdown. This is typically the result of the automatic, low point drains not operating properly or they are clogged with scale and rust.

### STEP 3 - Budget Review

#### Prioritization: Inspection, Repairs, Replacement

The ability (and necessity) to develop a plan of action that includes prioritization for inspection, repairs and/or replacements established from the unit specific design and historical operation will dramatically improve the budgetary process. Allotted funds will be used in an effective manner and outage planners will have the ability to provide "back-up" documentation required to warrant the necessity for such funding during the company's fiscal budget planning process.

#### Primary Deterioration Mechanism

Steel materials normally are subject to changes in microstructures when the steels are exposed to temperatures from 800 °F to 1000 °F. The changes in microstructure tend to relate to the maximum temperatures reached, and the time at the respective temperatures. If the temperatures are sufficiently high and the

stresses to which the header, steel pipe, welds, or tubes are subjected are of sufficient magnitude, dimensional changes may develop. Such dimensional changes at elevated temperatures are known as creep. Creep represents the permanent plastic deformation, which can occur at elevated temperatures and at stresses significantly less than the yield strength of the steel at the same elevated temperatures. Creep at elevated temperatures normally is categorized by a curve, which shows four portions (**Figure 3**). The first portion involves the initial extension (or expansion) at elevated temperature. This extension is partially elastic.

In the next stage, the extension (or expansion) rates decreases with time. This stage is also called a transient or primary creep stage. The primary creep stage is not considered to represent damage. Subsequently, a stage occurs on the creep curve located where the rate of creep (expansion) is nearly constant. This stage is also called secondary creep. The period of secondary creep after some expansion (i.e., in the latter period of the stage) is evidenced by initial void formation along the grain boundaries. In time, these tend to join or “link up.” Void formation generally tends to develop after approximately 50% of the life of the pipe material has been consumed. Thus, on the basis of the microstructures and the absence of any evidence of void formation, the high-energy piping would be expected to be suitable for another 200,000 hours of service.

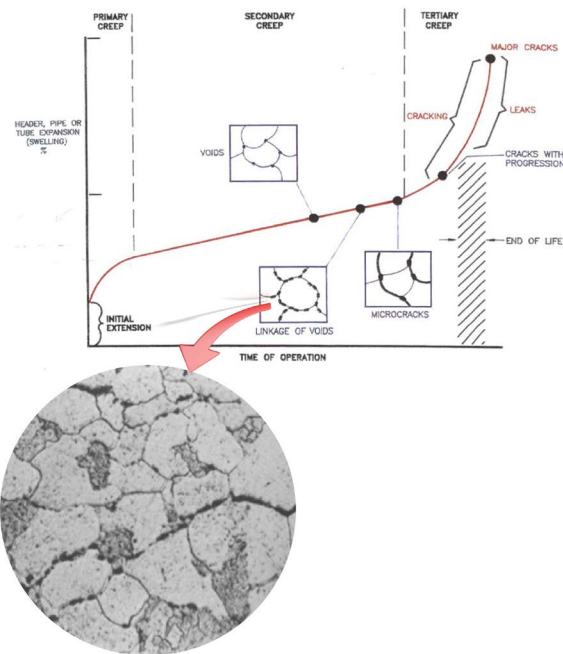
The fourth stage of the creep curve, located beyond the constant creep rate portion, involves a rapidly increasing creep rate. This stage is called tertiary creep. It involves grain boundary fissuring (or microcracking). After this stage is reached, the material would tend to develop failure. This may represent a “remaining-life” period of 5% to 10% of the prior operating period. Thus, when the header or pipe material reaches the tertiary creep stage, the end of the useful life of the steel material, at the specific area of high-stress levels, is being approached. In many components, the tertiary creep stage may not be reached until after 200,000 to 500,000 hours of operation, or longer. However, in other instances, particularly involving overheating of Superheater tubes, the tertiary creep stage has been reached after only 10,000 to 50,000 hours of operation. Such overheating, however, would generally involve temperatures of 1100 oF to 1200 °F. These are generally higher than the applicable design temperatures of most piping systems.

The results of stress rupture tests performed on samples removed from a high-energy piping system can provide information about the remaining useful life of a high-energy piping system.

To provide additional information regarding the condition of a high-energy piping system, the remnants of stress rupture samples are subject to metallographic examination. The observed microstructure will provide information about the condition of the piping system. Particular attention should be paid to the extent of carbide precipitation and agglomeration, as well as creep determinations (i.e.: void formation and void linkage or microfissuring).

### Outage Schedules

Facilities typically have an outage schedule to provide regularly scheduled maintenance and inspection of major components.



**Figure 3.** Stages of Creep Development. As creep stages progress, illustrated in the graph above, the voids begin to link with one another, developing into cracks which then propagate through the material eventually causing leaks or failures.

Short outages typically occur once a year and last about 7-10 days. Major outages typically occur every two-three years and last in upwards of 3-6 weeks depending on if replacements are scheduled or major overhauls of equipment are required. Developing a firm plan of action and having a concrete understanding of when and why these outages are scheduled can help allocate funding for prioritization of inspections and maintenance.

For example, if a plant is experiencing a valve leak, but is not scheduled for a major outage for another year, it may elect to do a “quick fix” or “band aid” type of repair to continue operations until the major outage. It is paramount that the problem be properly analyzed to ensure that the temporary repair strategy will be effective. This determination requires experience, expertise, and documentation of the components in question. All of this can be obtained by utilizing a unit specific strategic plan with a custom data management program.

### Budgetary Allocation

Alas, the budget. A common frustration among plant managers and planners occurs when the hurdles associated with identifying what needs done have been surpassed, yet retaining the appropriate funds becomes a challenge. Planners must justify the priority for the proposed funds and with that, clear documentation and professional support is essential.

Once the requested funds have been allocated, it must be utilized in the most effective manner with a clear plan of action. A unit specific plan and a real time management plan will not only maximize the return, but will also improve overall safety and reliability. Budgets can be justified when the system review and historical data have been retained and made readily available by way of a data management program.

## EPA Regulations

EPA regulations change constantly and facilities are faced with having to upgrade emissions or retrofit to meet these EPA regulations. Funding that would have otherwise been used for maintenance and inspection or replacements are then reallocated. A comprehensive unit specific strategic plan combined with a data management program will assist in early detection of a unit's remaining useful life cycle and/or identify solutions that could potentially void the need to decommission or upgrade. More and more facilities are being decommissioned rather than upgrading because the cost of performing the needed modifications outweigh the profitability of the unit's potential output.

## Remaining Useful Life Determinations

Determining the remaining useful life of critical components/tubing will allow for proper budgeting for replacements. Additionally, as systems begin to reach the end of their life cycle, more failures will inevitably begin to occur. Understanding when to "cut your losses" and replace sections will improve safety. Many factors can affect the life expectancy of critical components:

- Fuel type and quality
- Inadequate heat transfer
- Flow rate
- Water chemistry
- Thermal cycles
- Materials
- Proper hanger support
- Temperature excursions
- Proper attemperation
- Proper insulation
- Identifying and rectifying progressive indications

Understanding key factors associated with a specific unit that can ultimately contribute to shortening the life expectancy is paramount to predicting remaining useful life of critical components.

## Safety and Risk Management

Safety and risk management are highly regulated and are vital to a facility's success. A comprehensive program that focuses on operator training, maintenance and testing, as well as replacing components that have reached the end of their useful life, can reduce the risk of component failures within a power boiler. The need to create this custom plan is essential to the overall operation of the facility and most importantly the safety of the workers. Additionally, a progressive data management plan can offer extensive reductions in insurance costs as this establishes a proactive philosophy to prevent catastrophic events.

## Run, Repair, Replace

The presence of cracks invariably leads to decisions about run, repair, or replacement. However, the presence of surface cracks in a thick-walled component may not mean steam leak is imminent and, in certain circumstances, operation with cracks may be acceptable. Assessments in such cases depend on accurate crack growth data and analytical procedures described earlier. In view of the uncertainties in operating conditions and the lack of crack growth data on service-exposed material, many utilities opt for defect repair at planned outages. Clearly such options can only be

exercised if suitable weld repair procedures are available. Much research has been undertaken to improved weldment ductility by control of weld process variables to produce favorable microstructures or by modifications to weld metal composition.

As discussed, service experience often indicates that the first observable creep damage occurs as cracking at weldments. However, examination of weldments is not usually sufficient to ensure overall structural integrity. In many cases, welds can be successfully repaired without reducing the overall component life. When problems have been identified, alternatives to replacement sometimes exist.

Furthermore, even when replacement is inevitable, remedial action to allow continued operation may be necessary. A list of potential actions for common problems in critical components includes control of temperature ramp rates to minimize thermal stresses, maintenance of supports to minimize deleterious system loading, and proper control of welding processes and subsequent post-weld heat treatments. Such a list cannot be considered as comprehensive, but in general, when problems with creep damage have been identified, significant improvements in service performance are invariably derived by reducing peak operating temperatures and/or the rate of temperature changes. The penalties to efficiency resulting from such action are usually severe so that mechanical modification or alternative material selections are normally required.

Taking the above unit specific considerations into account when developing a strategic high-energy piping integrity program is essential to targeting the specific financial challenges a unit may be experiencing. Additionally, as the high-energy piping systems reach the end of their useful life, replacements should be planned. Replacing entire piping systems is typically not a cost effective approach, and would be impossible during a typical outage. Strategically planning for the replacement of specific spool pieces and utilizing an equipment management program is a more comprehensive and cost effective approach.

## CONCLUSION

### Modern and Proven Solutions

Thielsch Engineering, Inc. has spent the past 30 years working with America's power producers and advanced manufacturers to ensure safety, reliability and profitability. As James Chiles, Author of *Inviting Disaster* states, "Failure never happens out of the blue, it propagates from flaws that eventually link up." Because of this, every producing facility must have a system in order to manage the safety and integrity of their high-energy piping systems. The use of an effective data management plan/program, can provide control and solutions from anywhere in the world. The combined process of integrated engineering that includes unit specific education, observation, tracking, proper maintenance and data collection provides a modern approach to a complex and highly competitive market. ■

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## CONTRIBUTING AUTHOR



### **PAMELA HAMLIN**

Pamela Hamblin possesses 16+ years of experience with failure analysis and condition assessment within the utility industry. She is credited with the development and implementation of Thielsch Engineering's signature 4-SYTE System Strategy Program that is currently utilized in over 60 power plants across the United States. The 4-SYTE System Strategy Program offers utility companies an opportunity to integrate their boiler and piping components into a comprehensive management program. This modern software and customized service provides real time details that are critical to the continued production of power.