Expert Workshop on

Challenges and Solutions to implementation and reliable operation of Large-Scale Gaseous Hydrogen Infrastructure

July 31st and August 1st, 2024.

In collaboration with the ASME PVP Conference July 28th to August 2nd 2024
The Hyatt Regency, Bellevue, Washington, USA

As investment in clean energy technology accelerates, hydrogen infrastructure is increasingly considered an important element of a diverse renewable energy portfolio. Large-scale hydrogen infrastructure is already important in developed economies, but the scale required to displace conventional energy storage and transmission technologies will be orders of magnitude larger. This expert workshop on large-scale gaseous hydrogen infrastructure will explore the emerging needs of the engineering community to deploy hydrogen technologies at scale. The workshop will involve recognized experts active in research and development of hydrogen technologies. The presentations are organized in key topics from storage and transmission of hydrogen to fundamentals of hydrogen-materials interactions. Discussion in each session will be encouraged.

Wednesday, July 31st

1. Metallurgy / Hydrogen Fundamentals 14:45 – 16:00

1A: Towards a Virtual Hydrogen Lab: Computational predictions of hydrogen-assisted failures

Emilio Martinez-Paneda, University of Oxford (Oxford, UK)

Virtual Testing can be a game-changer in the deployment of a hydrogen energy infrastructure, enabling efficient and optimal component design, providing mechanistic predictions of material behaviour and fitness-for-service assessment, and preventing catastrophic failures. However, this highly sought ambition has long remained elusive due to the challenges associated with the complex multi-scale and multi-physics nature of hydrogen embrittlement. This work shows how those challenges can be overcome by improving our understanding of the physical phenomena at play, and by developing robust computational electro-chemo-mechanical schemes that can resolve the underlying physical processes.

A comprehensive finite element framework has been developed that can: (i) quantify hydrogen uptake from both gaseous and aqueous electrolyte environments, (ii) simulate the diffusion and trapping of dissolved hydrogen, and (iii) predict the nucleation and growth of cracks, assisted by hydrogen. This has been largely facilitated by the development of two computational technologies: coupled multi-physics models and phase field modelling. Predictions can be obtained for problems of arbitrary complexity (3D, multiple cracks, etc.), at both laboratory and component scale levels. Importantly, these predictions are obtained based purely on physical parameters that can be independently measured. The potential of the framework developed will be demonstrated by addressing two case studies of significant technological interest: (1) quantifying the critical pressure at which hydrogen can be transported in natural gas pipelines without leading to structural integrity issues in welds, and (2) conducting reliable virtual hydrogen-assisted fatigue crack growth experiments for arbitrary choices of loading frequency, material, load ratio, pre-charging condition, and hydrogen pressure.

1B: Heterogeneity and Risk Factors influencing Damage Susceptibility

Michael Gagliano and Jonathan Parker, Electric Power Research Institute (Palo Alto CA, USA)

EPRI have established an integrated approach to effective life management of critical components. This approach recognizes that excessive uncertainty in factors such as material microstructure and properties, operating conditions and how these factors change over time in service makes defining a practical assessment approach very difficult if not impossible. Moreover, it is well established that high levels of accuracy or confidence in a single factor cannot overcome variations in other parameters. Thus, EPRI recommends that a balanced approach linked to minimization of risk yields greatest value for resources invested. Hydrogen has been successfully moved and stored in dedicated structures for many decades, but factors associated with the build-out of a new hydrogen pipeline network, including cost, regulatory hurdles, and public opinion, have led to significant interest in leveraging the existing NG infrastructure for hydrogen service, which has evolved over time. With more than 50% of the existing US natural gas transmission pipelines built prior to 1970, there is considerable variability in the quality, condition, and pedigree of steel line pipe currently installed. To have confidence in best option decisions for major long-term investments, sources of variability that lead to uncertainty in performance must be understood and minimized. Understanding the factors affecting damage also allows the compositions and microstructures that are most susceptible to accelerated damage in hydrogen gas to be identified. This presentation will describe the approaches EPRI uses to characterize component microstructures and discuss how these variations can be linked to in-service performance.

2. Materials Compatibility 16:10 – 17:45

2A: Compatibility of Metals with Hydrogen Environments

Brian Somerday, Somerday Consulting, LLC (Wayne PA, USA)

The objective of this presentation is to provide a high-level overview of hydrogen embrittlement in structural metals. The first topics covered are the hydrogen-metal interactions at the atomic and micro scales that are essential elements in the hydrogen embrittlement process. Next, the macroscopic manifestations of hydrogen embrittlement are described through various mechanical property measurements performed in laboratory settings. Finally, variables affecting the macroscopic manifestations of hydrogen embrittlement are identified, and examples are provided for how these variables affect mechanical property trends. The importance of these variables for the management of hydrogen embrittlement in engineering practice is emphasized.

2B: Hydrogen-Materials Compatibility and Its Impact on Pipeline Integrity – An Industry Perspective

Joe Jun and Neeraj Thirumalai, ExxonMobil Technology and Engineering Company (Annandale NJ, USA)

In the emerging hydrogen economy, there is a growing need for pipeline transportation and an associated increase in hydrogen pipeline mileage globally. Hydrogen creates integrity challenges due to the phenomenon of hydrogen embrittlement. In this presentation we will discuss the mechanisms of hydrogen embrittlement in pipeline steels by comparing the behavior of sour service vs hydrogen gas pipelines. We will also highlight various technical challenges that needs to be addressed for successful repurposing of existing infrastructure as well new build pipelines for transporting hydrogen. These include integrity threats such as hard spots, definition of hardness limits, the mechanism of hydrogen entry in gaseous hydrogen pipelines, small scale vs full scale testing as well as the role of impurities and its impact on hydrogen pipeline operations. Finally, we will emphasize the importance of generating relevant data that provides the technical basis for the development and practice of codes and standards.

2C: Database of Hydrogen Compatible Polymeric Materials for Hydrogen Infrastructure

Shin Nishimura, HYDROGENIUS, Kyushu University (Kyushu, Japan)

Hydrogen uptake and volume change of polymeric materials are key parameters for designing high-pressure hydrogen seals and liners for type IV tank and dispensing hoses. The volume change of thermoplastic (semi-crystalline) polymers is generally smaller than that of rubber materials. In order to estimate much precise volume change, in situ volume change measurement system is developed. In the case of type IV tank, it is important to control permeation through liner materials. To estimate precise permeability, high-pressure steady state permeation test system is developed. The hydrogen related properties data of rubbers and thermoplastic polymers are summarized in database.

Thursday August 1st

3. Test Methods (fatigue and fracture) 8:15 – 10:15

3A: Influence of hydrogen kinetics on hydrogen-assisted fatigue and fracture testing

Joe Ronevich, Sandia National Laboratories (Livermore CA, USA)

Hydrogen-assisted degradation of mechanical properties manifests as the consequence of hydrogen diffusion in materials to regions of elevated stress. The observance of hydrogen embrittlement in a laboratory test can be influenced by time scales for hydrogen transport and by testing rate. Diffusivity of hydrogen can vary by many orders of magnitude in different materials and can be a rate limiting step for laboratory experiments. Limited hydrogen transport can be critical for accelerated laboratory testing as laboratory time scales (days to weeks) are generally much shorter than operational time scales where infrastructure is exposed to gaseous hydrogen for years or decades. Therefore, it is important to design appropriate testing conditions to capture the expected physics on the time scales expected in the field. Gaseous hydrogen can be introduced to materials via precharging prior to mechanical testing (internal hydrogen) or by in-situ exposure while mechanical loads are applied (external hydrogen). The rate of testing can influence laboratory measurements differently depending on the environment (internal vs external hydrogen) and these differences can be attributed to time scales for hydrogen transport. This talk discusses the role of testing rate on fatigue and fracture properties for austenitic stainless steels, pressure vessel steels, and pipeline steels with emphasis on the importance of the boundary conditions and time scales when extrapolating laboratory test results to performance of structures in hydrogen service.

3B: Ensuring transferability of mechanical test measurements in hydrogen gas to structural applications

Kevin Nibur, HyPerformance Materials Testing, LLC (Bend OR, USA)

The application of stress to metals while exposed to hydrogen gas can result in the formation and growth of sub-critical cracks, e.g. hydrogen embrittlement. Mechanical testing, specifically fatigue and fracture toughness testing, are necessary to generate the data that allow these interactions between hydrogen and metals to be predicted and to inform safe design of components. This presentation will address factors that need to be considered to ensure the test results are applicable to the final structural application. Specifically, impurities in the hydrogen gas such as oxygen and water may alter the test results leading to measurements that will not accurately predict the behavior of the final structural application. Additionally, the introduction of hydrogen into the material prior to testing, commonly referred to as hydrogen pre-charging, results in boundary conditions that differ from tests performed while the specimen is exposed to hydrogen. This presentation will briefly address how an understanding of the thermodynamics of hydrogen absorption and trapping can inform the choice of when each of these methods can be used to predict the behavior of the final structure.

3C: Hydrogen Test Methods: Past Present and Future

Robin Gordon, Microalloying International (USA)

As the interest in Hydrogen Pipeline increases there is a need to develop standard methods to perform fracture toughness and fatigue crack growth tests in Hydrogen environments that produce reliable material property results that can be used in the design and analysis of hydrogen pipelines.

This presentation will review the evolution of fracture toughness and fatigue crack growth test methods for hydrogen pipelines, identify gaps and make recommendations for standard Test Methods. The presentation will draw from experience with sour service test methods, which also address hydrogen embrittlement. Although Hydrogen Test Methods are still evolving sour service Test Methods have reached a level where standard industry accepted Test Procedures have been developed.

The presentation will also consider ECA procedures for hydrogen pipelines to enable fracture mechanics-based girth weld and seam weld flaw acceptance criteria to be established. Although most of the focus to date has been on evaluating seam weld performance in hydrogen pipelines the flaw tolerance in hydrogen pipelines will, in most cases, be limited by girth weld performance.

3D: Mechanical characterization of metals under Hydrogen pressure: current EU issues and developments

Laurent Briottet, French Alternative Energies and Atomic Energy Commission (CEA) (Grenoble, France)

During the past years, Europe has been enhancing its capacity to characterize the mechanical behaviour of metal alloys to support the development of an hydrogen infrastructure: increase of testing machines with pressure vessels, mechanical tests on hollow specimens, development of tests on small scale specimens. Many studies are under way to better understand and manage the influence of the testing mechanical parameters (geometry of the specimens, loading rate, …) as well as of the environmental conditions (effect of water vapour, O_2, H_2S content). The development of the best practices and standards to provide appropriate data for the design of Hydrogen infrastructures is one main objective. This is also supported by more fundamental studies to better understand and quantify the hydrogen embrittlement mechanisms supposed to be acting. The objective of this talk will be to present an overview of these developments with some focus on recent salient points of interests.

4. Hydrogen storage 10:30 – 12:30

4A: Overview of hydrogen storage systems and related challenges for the design of high-pressure vessels

Paolo Bortot, M. Ortolani, M. Bellingardi, Tenaris Dalmine (Dalmine, Italy)

Hydrogen is expected to play a prominent role and be one of the key ingredients in decarbonization and the energy transition process. Hydrogen possesses an elevated energy density per unit mass which is far superior to any common fossil fuels but on the other hand hydrogen in gaseous form has an extremely low density. Consequently, hydrogen needs to be either stored at high pressures or in very large quantities, compared to common hydrocarbon fuels, in order to achieve a comparable volumetric energy density.

Hydrogen refueling stations (HRSs) are an example of infrastructure where pressure vessels are designed to operate with hydrogen gas pressures up to 100 MPa and subjected to large pressure fluctuations that are needed to meet the consumers' demand for hydrogen fuel.

In addition to mobility applications, hydrogen has the potential to serve as an energy carrier for different energy sectors and for the decarbonization of hard-to-abate industries such as refineries, steelshops or ammonia plants and can be used to buffer the variability in renewable sources such as wind and solar.

The intermittent nature of such sources cannot be easily accommodated in the current energy grid and additional grid flexibility is required through large energy storage systems. Such systems should be capable to store hydrogen to a much larger extent in terms of storage volume, although to lower pressures (typically not higher than 350 bars), compared to the ones used in HRSs for mobility purposes.

Traditionally, gaseous hydrogen has been stored in low alloy high strength ferritic steel vessels, despite the fact that such materials can suffer degradation due to hydrogen embrittlement (HE) [1-2]. In order to cope with this effect and provide safe design methodologies, design codes have developed a variety of approaches. Among them, the only fracture mechanics-based approach is prescribed by ASME Boiler and Pressure Vessels Code (BPVC) Section VIII Div.3, art. KD-10 [3]. This approach requires both fatigue crack growth rate (FCGR) and fracture toughness (FT) measurements to be performed in the targeted design environment and pressure. As of today, this is probably the most widely adopted design method for high pressure hydrogen container vessels.

In HRSs, where hydrogen gas is stored at high pressure, seamless pressure vessels are used and there is extensive engineering experience using quenched and tempered (Q&T) Cr-Mo and Ni-Cr-Mo steels, such as the ASME SA-372 grades. In recent years, these materials have been extensively investigated and characterized for fatigue crack growth and fracture toughness [4-6] in high pressure hydrogen gas conditions. FCGR curves for these grades are published in the ASME BPVC Code Case (CC) 2938-1 [7].

However, large storage systems cannot be fabricated with integrally forged vessels, due to the intrinsic limitation in the capability to manipulate a single, large seamless forging. In these applications, large pressure containers can be designed and built efficiently by joining multiple seamless pipes through girth welds [8].

This work provides an overview of the design challenges associated with the fabrication of seamless and welded pressure vessels operating in hydrogen gas environment.

First, the established knowledge on traditional Q&T low alloy steels is reviewed, including new pressure correction factors that are under evaluation for inclusion in existing ASME BPVC CC 2938-1 [7].

Secondly, very recent fatigue and fracture data generated on weldable, high strength steels will be presented and discussed along with recommendations for welding high strength materials for hydrogen gas applications.

References

1. C. San Marchi, B.P. Somerday, Technical Reference for Hydrogen Compatibility of Materials. Report no. SAND2012-7321. Sandia National Labs, 2012.
2. R. Gangloff, B.P. Somerday, Gaseous Hydrogen Embrittlement of Materials in Energy Technologies, Woodhead Publishing, 2012.
3. ASME BPVC Section VIII-3, art. KD-10.
4. San Marchi C. et al., Fatigue and fracture of high-hardenability steels for thick-walled hydrogen pressure vessels. International Conference on Hydrogen Safety (ICHS), Hamburg, Germany, 2017.
5. San Marchi C. et al., "Technical basis for master curve for fatigue crack growth of ferritic steels in high-pressure gaseous hydrogen in ASME Section VIII-3 code (PVP2019-93907)," ASME Pressure Vessels & Piping Conference, San Antonio, TX, 2019.
6. Bortot P. et al., Effect of Hydrogen Partial Pressure on Fatigue Crack Growth Rates of Low Alloy, Quenched and Tempered Steels (PVP 2023-106417), ASME Pressure Vessels and Piping Conference, Atlanta, GA, 2023.
7. ASME BPVC CC 2938-1.
8. Bortot P. et al, Welding high strength ferritic steels for hydrogen service, presented at the International Hydrogen Conference 2023, Park City, USA.

4B: Subsurface Storage of Hydrogen – Hurdles in the Path Forward

Mathew Ingraham, Sandia National Laboratories (Albuquerque NM, USA)

Large scale adoption of hydrogen as a low/zero carbon fuel, will require a significant rework of existing subsurface storage infrastructure. Most existing subsurface storage is used for natural gas, which in the case of depleted reservoirs and brine aquifers, is what was most likely stored in the rock void space prior to removal by human action. Therefore, reinjection of natural gas will have little consequence on the geochemistry, microbiome, or geomechanics of the site. Introduction of pure or blended hydrogen to the subsurface has the potential to react with subsurface minerals and fluids potentially affecting strength, and pore structure. The subsurface microbiome, in the presence of pure hydrogen has the potential to both consume and contaminate the stored gas. Conversion to hydrogen will also require development of multiple new storage fields as the relative energy density of hydrogen is low compared to natural gas.

The SHASTA (Subsurface Hydrogen Assessment, Storage, and Technology Acceleration) project, a collaboration between The National Energy Technologies Lab, Lawrence Livermore National Lab, Sandia National Labs, and Pacific Northwest National Lab, is working to determine the viability, safety, and reliability of storing pure hydrogen or hydrogen-natural gas blends in subsurface environments. This includes investigations of geochemistry, microbiology, geomechanics, economic analysis, public acceptance, wellbore integrity/materials (steel, concrete, polymers).

4C: Challenges and Solutions with Bulk Storage of Hydrogen

Rob Trautz, Electric Power Research Institute (Charlotte NC, USA)

Large-scale hydrogen use for electric power generation and industrial processes will require bulk hydrogen storage on a scale comparable to that deployed today for natural gas. Few options exist for storing very large volumes of hydrogen needed to satisfy future industrial demand that (based on the need to displace natural gas) could approach a million metric tonnes per year (Mt/yr) or more. Hydrogen's low volumetric energy density at normal working temperatures and pressures, and very low boiling point, create significant storage challenges. Liquefaction of hydrogen and subsequent storage in above ground storage tanks is expensive, consuming about 30 percent of the energy content of the hydrogen. Underground storage of hydrogen is a second option currently in use for natural gas that shows promise but faces significant challenges too. Repurposing existing U.S. underground natural gas storage fields for hydrogen storage could potentially provide upwards of 10 Mt-H_2 of storage, which represents only one-quarter of the energy stored in natural gas in these same fields. Eighty percent of the existing underground storage facilities consist of depleted natural gas fields that will serve to contaminate any hydrogen stored in the same facilities. Other challenges and solutions will be explored further during the presentation.

5. Hydrogen Transmission Pipelines 13:30 - 15:30

5A: Hydrogen and the pipeline network - a European perspective

Marion Erdelen-Peppler, Rosen Group/European Pipeline Research Group (Germany)

Europe has laid out its plans for a hydrogen economy as a major contributor to reach the anticipated climate goals. By 2040 there will be a pipeline network consisting of more than 50.000km of high-pressure hydrogen transmission lines. The majority of these will be repurposed pipelines but plans also include significant new builds on- and offshore. To reach these ambitious goals, the existing knowledge gaps need to be closed. Within this context, research organisations play a major role to focus the work and make best use of the limited international research capacity. This presentation will outline the current status of ongoing projects in Europe, especially those in which the European Pipeline Research Group EPRG is involved. Amongst other findings, it is expected that progress will have been made on the understanding of how small-scale tests correlate to full scale behaviour of pipes, and on suitable assessment methodologies.

5B: Integrated Lifing Strategy for Building New and Repurposing Existing NG Pipelines

Shane Finneran and Ramgopal Thodla, DNV Columbus (Dublin OH, USA)

Decarbonization of existing energy systems is a key objective of the global energy transition. Hydrogen is increasingly viewed as a necessary carbon free fuel and energy carrier to enable decarbonization. The expansion of a hydrogen infrastructure is therefore critical to support this development. Pipelines have been proven to provide efficient and reliable transportation for large volumes of gaseous products, there is currently significant interest in developing a framework for the design and operation of pipelines for hydrogen gas service, considering both new build and conversion of existing pipelines. Hydrogen is a recognized embrittling agent for most metallic materials, including steels commonly used in existing pipelines. Gas pipelines are typically subject to high mean loads due to high pressures as well as fatigue loading due to variable operation load cycles. The presence of hydrogen under these loading conditions can lead to significant degradation in the material performance. Therefore, it is necessary to understand the conditions under which embrittlement is likely to occur and quantify the impacts on material performance to determine how to effectively mitigate these impacts and enable safe and reliable transportation of hydrogen.

The work presented summarized the findings of ongoing material testing, addressing the impacts of hydrogen on material performance, including fracture toughness (FT) and fatigue crack growth rates (FCGR). The Paris curve behavior in high pressure hydrogen on the FCGR behavior has been evaluated on several pipeline steels. However, there is very little information on the near threshold FCGR behavior, which is critical in performing assessments for gas pipelines. Recent work has explored the factors that influence the FCGR near ΔK_{th} and its application to engineering assessments will be discussed. The fracture resistance of steels in high pressure H_2 is significantly lower than in-air. However, the exact definition of the fracture toughness in environment is not well defined, the recent work performed using the rising displacement methodology provides insight into the initiation fracture toughness behavior. The effect of various factors on the initiation fracture toughness and its impact on engineering assessments will be discussed. In addition to deterministic engineering analysis a framework to incorporate probabilistic approaches to engineering assessments is also discussed.

5C: Hydrogen Blending – Evaluating the Impact on Gas Transmission Pipeline Integrity

Scott Riccardella, Structural Integrity Associates, Inc (Denver CO, USA)

Hydrogen is widely recognized as a viable, clean alternative energy carrier. Recent advances in technology for clean hydrogen production, as well as renewed governmental and organizational commitments to clean energy, have intensified interest in utilizing the existing natural gas pipeline infrastructure to transport hydrogen from production sites to end users. Energy companies are pursuing strategic pilot programs to evaluate the capacity of their natural gas transmission and distribution pipeline systems to safely transport blends of natural gas and hydrogen. These pilot programs demonstrate the commitment of energy companies to facilitate environmentally responsible energy production and consumption while identifying and investigating potential challenges to pipeline safety and integrity associated with hydrogen blending. This session will present an overview of the key threats to gas transmission pipeline integrity likely to be impacted by blending hydrogen with natural gas (hydrogen blending) and provide a risk framework for the evaluating the impact to these integrity threat.

5D: An overview of the Hydrogen Extremely Low Probability of Rupture (HELPR) toolkit for probabilistic structural integrity assessments when transporting hydrogen in natural gas infrastructure

Ben Schroeder, Sandia National Laboratories (Albuquerque NM, USA)

The Hydrogen Extremely Low Probability of Rupture (HELPR) toolkit is a publicly available open-source software developed at Sandia National Laboratories as part of the Hydrogen Pipeline Blending CRADA, a Department of Energy HyBlend™ project. HELPR is motivated by the need to assess the structural integrity threat posed by blending hydrogen into natural gas transmission and distribution infrastructure. A modular software structure is utilized to develop HELPR's Python backend and graphical user interface. The modular design enables agility in specifying analysis workflows, eases the additional of models and capabilities, and simplifies testing and development. Hydrogen effects on structural integrity are accounted for within HELPR through material properties including crack growth rates and fracture resistance. HELPR provides probabilistic capabilities enabling a richer understanding of the inherently probabilistic nature of structural integrity assessments. Engineering models with low computational costs, such as those specified in ASME B31.12 and API579, are used to make fatigue and fracture predictions. The low computational costs allow the probabilistic framework to propagate input uncertainty characterizations through the models using Monte Carlo approaches to generate predictions with characterized uncertainty as well as to analyze the sensitivity of predictions to the input parameters. HELPR enables users to explore infrastructure design, operating conditions, and inspections in terms of impact on structure integrity and risk. HELPR's underlying capabilities, supported analysis types, as well as user experience with the user interface are all being continually developed based on user feedback.

6. **Case Studies** **15:45 – 17:45**

6A: Challenges and Solutions to Transmission of Hydrogen in the UK

Robert Best, National Gas Transmission, Plc (Warwick, UK)

The United Kingdom has set an ambitious target of eliminating net carbon emissions by 2050 and a wide range of green technologies are required to reach this goal. One key technology is hydrogen as an alternative for carbon fuels in heat, transport, and industry. *National Gas Transmission Plc,* as the owner and operator of the National Transmission System (NTS) in Great Britain, is supporting the transition to hydrogen via the creation of a 100% hydrogen backbone, known as *Project Union*, linking industrial producers and users throughout the country via a largely repurposed network of high-pressure pipelines. However, the NTS was not designed to transport hydrogen, and as such, a programme of work has been developed to understand and manage the impact of hydrogen on the pipeline assets.

The approach to repurposing the NTS will be discussed in the context of key projects undertaken at *National Gas Transmission* to understand and assess the capability of the network to transport high-pressure hydrogen. A summary of the extensive materials test programme and detailed characterisation work on ex-service and new pipeline steels will be presented alongside a review of technologies considered to mitigate the detrimental effects of hydrogen on metals.

6B: Repurposing Natural Gas Pipeline Infrastructure for Hydrogen – A Case Study in a Phased Approach to Assessment and Planning for Hydrogen Conversion

Craig Clarke, GHD (Auckland, New Zealand)

Existing natural gas infrastructure provides a significant opportunity to support the accelerating journey to decarbonize energy supply chains. Assessment of conversion costs compared with new asset development has found that repurposing can be completed at a fraction of the cost, and in shorter timeline, than new infrastructure build.

Repurposing provides a pathway to support decarbonization of existing molecular energy users with the added benefits of reduced access and approvals risks, accelerated schedule, and minimizing community and stakeholder disruption.

A recent screening assessment of the asset base of Australia's largest onshore natural gas pipeline owners' infrastructure found that almost half could be repurposed for hydrogen service with minor or no changes in operating envelope. The remainder would be subject to more detailed assessment and testing and a reduction in MAOP is expected be needed to manage integrity in H2.

The screening tool was developed to identify the suitability and capability of existing pipeline infrastructure to transport hydrogen and evaluate the potential changes in operating envelope that may be required for safe reliable operation. The multicriteria screening tool allows rapid evaluation of asset portfolios to assess the likely suitability for hydrogen service, the anticipated extent of inspection and testing required, and potential extent of changes to operating envelope.

Screening forms the first step in optioneering supplemented by commercial review to form a short list of candidate pipelines. Shortlisted candidates then enter preliminary desktop and fatal flaws assessment, followed by baseline evaluation and preliminary conversion plan development, and finally a detailed technical assessment and fitness for purpose evaluation, detailed conversion planning, and inspection and test plan finalization. Through each iteration a go/no-go assessment is completed considering technical risk, commercial requirements, and opportunity development.

In each phase more detailed inspection, testing, and engineering assessment are completed to obtain more detailed understanding of repurposing requirements, risks, and operating envelope changes. Phase 1 entails detailed characterization in air in combination with literature based hydrogen factors and pipeline records to complete preliminary assessment of the operating envelope and conversion plan requirements. This allows hydraulic capacity assessment and initial cost estimate development for commercial evaluation of project viability.

Phase 2 utilizes detailed testing in the hydrogen environment to characterize the line pipe performance in hydrogen service which is used to complete detailed engineering assessment, fitness for service review, and risk assessment to finalize the conversion plan requirements. Phase 3 entails the implementation of the conversion plan requirements including final inspection, testing, and verification works, and system modifications and upgrades for hydrogen service.

This case study will overview the phased approach to repurposing starting with the screening approach applied to evaluate a pipeline companies asset base of 18,000km of pipelines to identify repurposing opportunities. This will be followed by an example of the subsequent stages of evaluation on an identified opportunity using the Pamelia Gas Pipeline hydrogen conversion project. Finally, a review of the value proposition of repurposing over new infrastructure through a simplified example of the overall cost and schedule impacts to an existing conversion project.

6C: Hydrogen Initiatives at Southern Company Repurposing Natural Gas Pipeline Infrastructure for Hydrogen – A Case Study of the Approach, Opportunity, and Challenges

Chet Acharya, Southern Company Gas (USA)

Hydrogen can play an important role in achieving the net-zero greenhouse gas emission goal of Southern Company by 2050. By leveraging the existing expertise and infrastructure of the gas and electric operating companies, Southern Company can play an important role in developing a clean, safe, reliable, and affordable hydrogen economy. Southern Company Gas has the expertise and capabilities to move and store natural gas, which can be used for hydrogen in the future. However, the impact of hydrogen on the entire value chain should be well understood. Southern Company is leading and participating in several initiatives to understand the impact of using hydrogen in the existing system and to explore new opportunities with hydrogen.

Nicor Gas, a subsidiary of Southern Company is a participant of the Midwest Alliance for Clean Hydrogen (MachH2) hydrogen hub. Southern Company is a part of various initiatives such as HyBlend and SuperTruck 3, and through organizations such as GTI, NYSEARCH, Pipeline Research Council International (PRCI), and Electric Power Research Institute (EPRI). In 2022, a successful test burn was performed on 20% by volume of hydrogen in natural gas at Plant McDonough Atkinson. These types of initiatives are improving our understanding and capabilities with hydrogen.

6D: Consensus Engineering Requirements for High Pressure Hydrogen and Hydrogen Blend Transmission Pipelines

Simon Slater, ROSEN Integrity Services (OH, USA)

The natural gas industry is swiftly adapting to the evolving energy landscape. In the last five years, there has been a significant increase in focus and research from Natural Gas pipeline operators, looking at how to build and repurpose high pressure transmission pipelines to economically move hydrogen and hydrogen blended gas. Gaps have been identified in the current technical standards for design, operation, and maintenance of hydrogen pipelines, and repurposing of natural gas pipelines for hydrogen. Substantial research has been conducted in the hydrogen pipeline space, and the current state of the art must be translated into best practice requirements, codes and standards. The American Society of Mechanical Engineers (ASME) agreed that an update to ASME B31.12 was required, for hydrogen and hydrogen blend pipelines. The update would be performed by moving the guidance for pipelines to ASME B31.8 as an exception chapter, mirroring what has been done for sour service gas and gaseous CO_2.

The Emerging Fuels Institute (EFI), established by the Pipeline Research Council International (PRCI), developed a project to create Consensus Engineering Requirements (CERs) for hydrogen and hydrogen blend pipelines. The CERs set out the requirements for high pressure pipelines, in addition to those for lower pressure applications. The CERs will be used as the basis for the ASME B31.8 exception chapter. The intention is to progress the CERs through the ASME review process for publication in the 2026 edition of ASME B31.8.

The CERs are predicated on the latest research related to pipeline transport of hydrogen gas and blended hydrogen gas developed by global industry expertise. The CER project team consisted of over 40 members, the majority of who are gas pipeline operators. The group worked in close collaboration with key stakeholders, including the tripartite members of PRCI, European Pipeline Research Group (EPRG) and Australian Pipeline Gas Association (APGA), and the ASME B31.12 and ASME B31.8 committee.

This presentation will include a summary of the work performed and the approach taken to develop consensus through collaboration with key stakeholders. A number of the key technical issues that were resolved by updating guidance and requirements will be discussed, and the rationale supporting the changes presented.

6E: Modern Failure Assessment Diagrams (FADs) for Defect Assessment in Pressurized Ferritic Steel Components

Robert H. Dodds, University of Illinois at Urbana-Champaign (CO, USA)

The presence of hydrogen complicates the integrity assessment for crack-like defects in new and re-purposed pressurized structures constructed of ferritic steels. Failure Assessment Diagrams (FADs), as described in API-579-1//ASME FFS-1 (2021) and similar international standards, document accepted procedures for engineering-based evaluations. At a minimum, hydrogen can impact the material toughness measures employed in conventional FAD-based assessments.

A FAD curve defines an approximate value of the crack-driving force for brittle and ductile fracture from linear-elastic to fully plastic deformation levels. FAD curves have the form $K_r = F(L_r)$, where $K_r = \sqrt{J_e/J}$ and L_r is a non-dimensional measure of the applied loading relative to a reference yield load. Here, J denotes the elastic-plastic J-integral, with J_e the linear-elastic component of the total J, and $K_I = \sqrt{EJ_e/(1-\nu^2)}$. $K_r = 1.0$ at $L_r = 0$ and decreases non-linearly as L_r reaches 1.0 and beyond. Using the material toughness for in-service conditions (K_{mat}), K_I and L_r for the specific crack and loading level, an assessment point is plotted relative to the FAD driving force curve.

To have general application, the API -579 Level 2 FAD curve, $F(L_r)$, represents the driving force for a generic geometry, crack shape/size, loading type (*e.g*. tension, bending, ..), and material flow properties. The normalization using *J* and L_r aims to reduce the dependence of $F(L_r)$ on these quantities. The functional form of $F(L_r)$ in standards has evolved through several decades of revisions to better capture the transition from linear-elastic to fully-plastic conditions, *e.g.* API-579 Level 3 incorporates the specific material flow properties. Other enhancements in the FAD approach incorporate constraint (triaxiality) effects, strength mismatch in welds, thermal and residual stresses, probabilistic effects, etc.

Despite these advances, the API-579 Level 2/3 FAD curves remain generic and necessarily strive to be conservative (larger driving force). The level of conservatism, however, may vary widely when applied to specific cases. Moreover, details of the curve shape play a key role in ductile instability analyses – the general shape may be unsatisfactory.

To address these issues for pressurized ferritic steel components, the Electric Power Research Institute (EPRI) commissioned a new effort to create a modern version of the Elastic-Plastic Fracture Handbook[1]. To date, 19,000 3D nonlinear finite element analyses have been completed for a wide range of crack sizes and locations in varying sizes of cylindrical shells, flat plates, and piping elbows. Strain hardening levels for all configurations include *n* = 3, 5, 7, 10, 15. Each 3D analysis produces the full *J* vs. loading history expressed as a FAD curve $K_r = F(L_r)$ at the maximum *J*-value on the front for that specific geometry, material hardening, crack size-shape-location and loading type (pressure, axial, bending, combined). An EPRI report describes the methodology, an improved form of $F(L_r)$ fit to the finite element results, and details of the massive computational effort. For applications, a graphical-based PC program provides the curve-fit results to $K_r = F(L_r)$ in a readily accessible form.

The presentation briefly describes the FAD approach and selected results from the EPRI sponsored project.

1. T.L. Anderson, R.H. Dodds, G.V. Thorwald, T. Dessein, D.J. Shin. Development of a New EPRI Elastic-Plastic Fracture Mechanics Handbook. Proceedings, ASME Pressure Vessels & Piping Conference, PVP2023-106341, 2023.