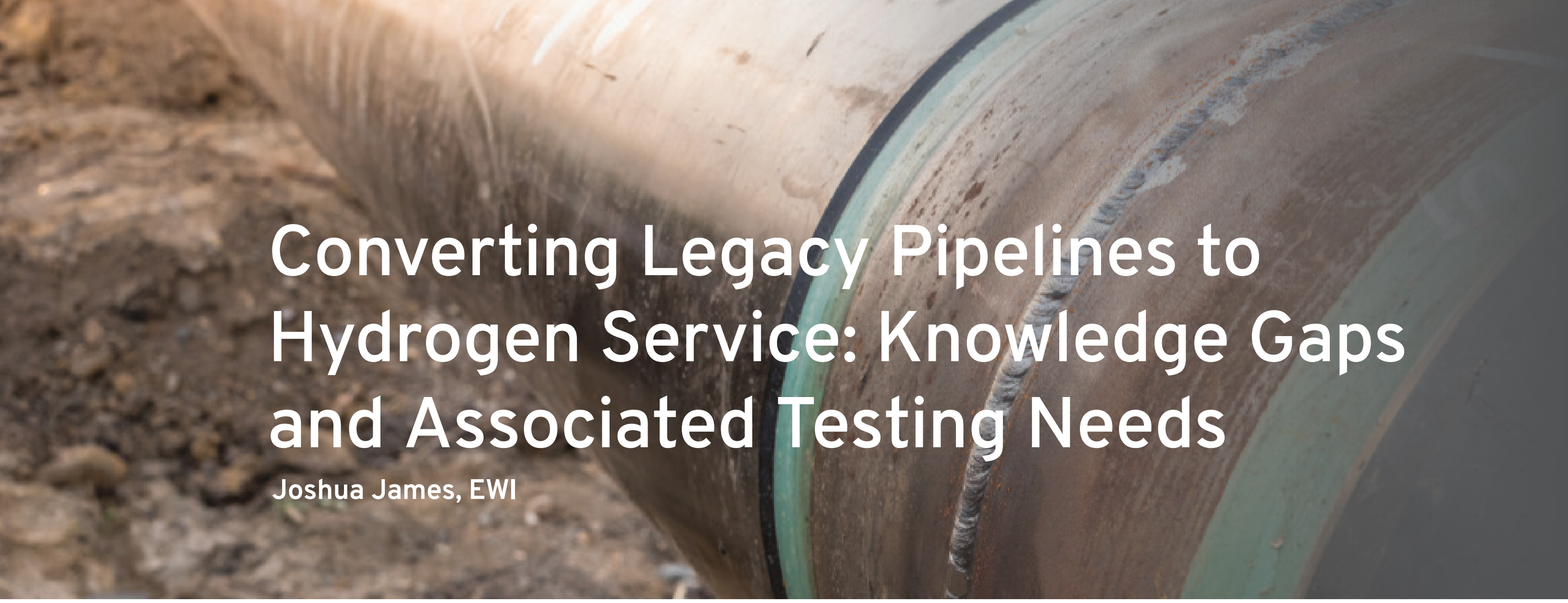
Converting Legacy Pipelines to Hydrogen Service: Knowledge Gaps and Associated Testing Needs



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Due to several coinciding economic, environmental, and regulatory factors, hydrogen is re-emerging as an attractive fuel source for future industrial and retail applications. The current fossil fuel-based energy market is under pressure to develop sustainable, non-carbon sources to address growing climate and policy-maker concerns. Hydrogen has attributes that may mitigate some of these concerns and offer opportunities to accelerate the transition to "green" energy consumption. These advantages include the following:

- ***Carbon neutrality***: Hydrogen burns cleanly and free of carbon emissions.
- ***Long-term energy storage:*** Hydrogen is an alternative to batteries for longer term energy storage.
- ***Low cost of hydrogen production:*** The decreasing costs of solar and wind energy contribute to affordable production of "green" hydrogen.
- ***State legislation and support for energy programs:*** Some examples include California's natural gas regulation and hydrogen utility incentive programs in Hawaii and Utah.

Forbes Business Insights has reported a projected hydrogen economy on the order of $200B by 2027.[1] With steadfast investment in lowered carbon emissions and non-fossil fuel sources for energy production by European and Eastern Asian countries. The Wood Mackenzie Group forecasts the cost of "green" hydrogen to decrease by 64% by 2040 projecting the hydrogen economy size to well over $1T in that time frame.[2] To reach this level of economic influence, hydrogen will need to be produced, transported, and consumed as fuel in a conventional utility paradigm across industries, as seen in Figure 1.

Switching to high hydrogen fuel sources, however, is not trivial. Market drivers aside, principal technological concerns involve hydrogen-related integrity threats to infrastructure, especially if legacy pipelines are to be

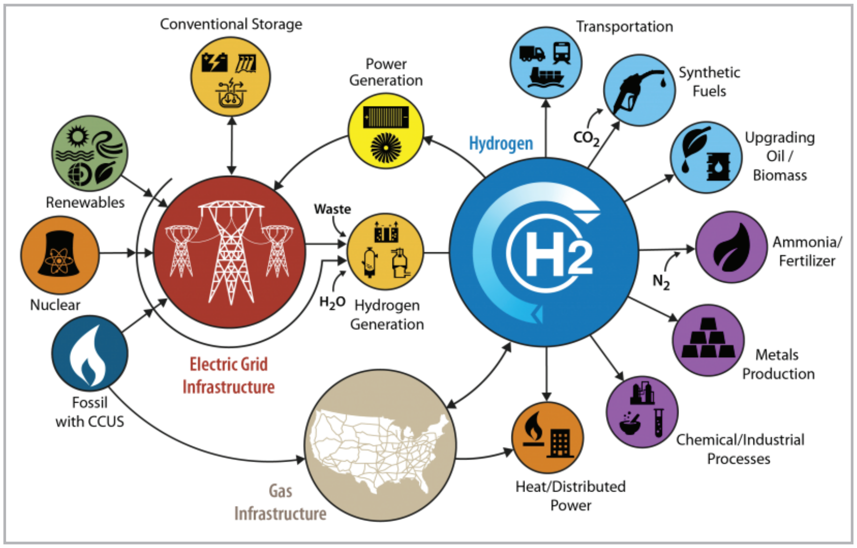

Figure 1. Diagram exploring utility scale use of hydrogen. (Source: US DOE – Office of Energy Efficiency and Renewable Energy - H2@Scale)

converted for transportation. Pipeline operators (primarily natural gas) are faced with fitness-for-service uncertainty when considering the switch to hydrogen gas blends in their transportation networks. To provide confidence in the face of a seemingly inevitable shift toward hydrogen as a utility fuel, further research and understanding are required by industry partners to ensure safe operation of pre-existing and new construction pipelines and storage facilities.

Knowledge Gaps

The economic boon promised by a transition to hydrogen is hindered by knowledge gaps along the path to sustainable viability. Chief among the areas that require more data and research is the transportation of hydrogen fuel from source to end-use. The typical midstream strategy is to convert legacy natural gas pipeline infrastructure to transport high hydrogen fuel blends. This, however, requires re-assessment from a materials integrity standpoint, as introducing hydrogen to pipeline construction materials can greatly alter their expected resistance to degradation and failure mechanisms. The potential threats and concerns are varied and often synergistic, but some primary drivers are as follows:

Fatigue/Fatigue Crack Growth – Very little data exists on endurance fatigue curves for pipelines transporting hydrogen blends. There is also a lack of fatigue crack-growth data for blended hydrogen in natural gas at various percentages and loading ratios typical of transmission and/or distribution operations. The fatigue properties of the pipe body will likely vary considerably from those of the girth or seam welds and their heat affected zones. Seam welds are likely to experience greater fatigue concerns than girth welds under operational pressure cycles and, depending on seam weld type and vintage, those fatigue properties may vary significantly.

Toughness – For pipeline steels, accurate values of toughness as a function of steel composition and processing methods at various levels of hydrogen fuel blending is not readily available. This data must be developed to evaluate the potential impact of hydrogen embrittlement in reducing material toughness on damage assessment models. In addition, the significance of local toughness variability associated with different seam weld types is unknown. Toughness evaluation will likely have implications for establishing reasonable inspection intervals and flaw detection limits.

Aging Components – More study is needed to understand the anticipated impact of vintage metallurgy, existing damage and repair histories, and mechanism synergy when converting to hydrogen fuel blends and establishing operating thresholds. This includes the potential coupling of multiple damage mechanisms or acceleration of damage rates under hydrogen service. These factors could reduce existing safety thresholds commonly used in the pipeline industry. Evaluation will influence approaches for repair, rehab and maintenance of aging infrastructure that is subjected to hydrogen service.

Understanding the Threats

EWI has a long history of validating material properties for service. As the need for a better understanding of the effects of high hydrogen environments becomes increasingly apparent, EWI is leveraging its experience, materials testing capabilities, and structural integrity expertise to provide evaluation solutions. Regarding pipeline infrastructure conversion for high hydrogen fuels, there is a diverse set of variables that will need to be tested and qualified over the range of applicable hydrogen fuel blends to fully understand impact. Some of those variables are:

- ***Material Characteristics:*** Steel grade, pipe vintage, pipe diameter and wall thickness
- ***Metallurgical History:*** Alloying impurity levels with respect to vintage, corrosion wall loss, fitness-for-service applicability
- ***Damage Mechanism Synergy:*** Third-party damage, previous repairs, construction defects, embrittlement, hydrogen-assisted stress cracking

Introducing hydrogen fuel blends to pre-existing natural gas transport and storage infrastructure will likely influence materials degradation and introduce new integrity threats not associated with natural gas transportation. These factors will need to be considered for future operating inspection, maintenance, and integrity management plans.

Primarily, hydrogen-related failure mechanisms (embrittlement and hydrogen-assisted cracking) and their synergistic effects on propagating other degradation mechanisms are the most prominent threats in converted pipelines. Figure 2 illustrates how the hydrogen proton infiltrates the metallic component, collects at discontinuities in the microstructure, and produces defect coalescence which, in turn, degrades the mechanical properties and can result in premature failure.

These threats to material integrity are uniquely prominent in hydrogen environments. Developing reliable test data to assess the influence of hydrogen-rich environments on material integrity is, thus, paramount for the future of the hydrogen utility. The goal of future testing and data collection efforts should be to answer the following questions:

- *At what blend level does cracking significantly increase in severity and/or frequency?*
- *At what blend levels should certain steel materials be no longer considered appropriate due to increasing or unpredictable risk?*
- *Which factors have the greatest influence on long-term impacts of hydrogen exposure in pipe steels?*
- *Could tolerance limits for mechanical damage and other forms of unplanned in-service loadings be reduced at certain hydrogen exposure levels?*
- *Could typical pipeline inspection intervals become non-conservative above certain hydrogen exposure levels?*
- *How does the above change with respect to metallurgical and damage history of legacy infrastructure?*

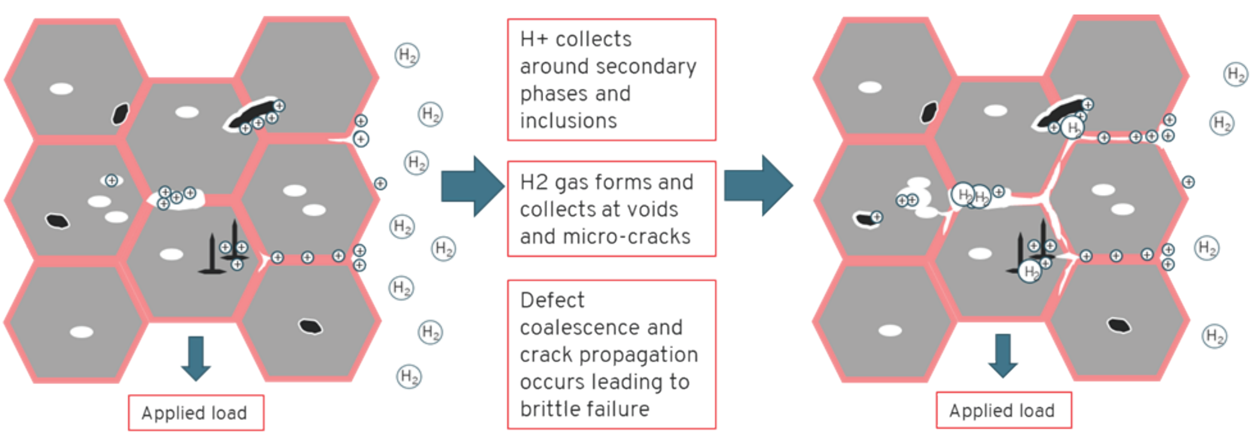

Figure 2. Schematic detailing the hydrogen embrittlement mechanism in steels.

Ultimately, targeted testing plans will lead to the development of a high-level relationship between toughness, crack growth, operating pressure, and percent hydrogen blend as a function of pipe grade, vintage, and pipe manufacturing method.

EWI's Dedicated Hydrogen Test Lab

EWI is advancing plans to build a dedicated hydrogen test laboratory in its Columbus, Ohio, facility. This lab will initially provide fracture toughness testing to determine limiting toughness values for the range of materials and conditions discussed above. Standard small-scale test specimens (compact tension, single notch bend, etc.) will be prepared and tested under a wide range of hydrogen environments to characterize the effects on material toughness. The lab will have the capacity to run multiple tests concurrently under a variety of hydrogen environments and loading conditions.

Lab capability will be expanded in further phases to include fatigue testing under hydrogen environments and other associated dynamic test protocols that may be of interest to characterize the influence of hydrogen more fully. Some additional test capabilities will include strain aging, notched tensile and Charpy V-notch impact tests to characterize various effects on ductility under hydrogen environments. Weld cold cracking susceptibility tests and measurement of hydrogen absorption into weld deposits made on hydrogen-charged steels will provide guidance on repair welding operations. In addition, testing and evaluation of the effects of hydrogen on polymers, elastomers, and composites will be possible. This area of non-metallic testing will establish damage and operating limits for a wide range of seals, gaskets, coatings, and non-welded repair practices used in many industries.

Path Forward

Moving toward the emerging hydrogen energy economy requires assurance that pipeline infrastructure will be both safe and long lasting. Rigorous testing and evaluation are necessary to fully understand the relationship between hydrogen-assisted degradation and the typical materials integrity variables in vintage natural gas pipelines. These results can then be used to affirm weld-flaw acceptance criteria, assess the validity of fitness for service rules, and inform inspection and maintenance procedure adjustments.

The impact of hydrogen blending on susceptible components over time is currently not well-established; The development of this knowledge base is critical to fully understand the long-term impacts on infrastructure/ material lifetime and to ensure safety and economic health in a hydrogen future.

For further discussion, please contact Josh James at **jjames@ewi.org**.

Note: *Any reference to specific equipment and/or materials is for informational purposes only. Any reference made to a specific product does not constitute or imply an endorsement by EWI of the product, or its producer or provider.*

References

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Joshua James *is Principal Engineer and Research Leader for the materials and structural integrity group at EWI. He applies his extensive experience in materials degradation to both internal EWI research and client projects related to corrosion and materials science. Josh holds a patent for a corrosion inhibiting coating additive and has authored several publications on his research.*