CAAP Quarterly Report

07/06/2025

Project Name: "Accelerating Transition towards Sustainable, Precise, Reliable Hydrogen Infrastructure (Super-H2): Holistic Risk Assessment, Mitigation Measures, and Decision Support Platforms"

Contract Number: 693JK32250007CAAP

Prime University: North Dakota State University

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Reporting Period: 03/28/2025 – 06/27/2025

Project Activities for Reporting Period:

In this quarterly report, the research teams continued to organize and conduct routine biweekly meetings to coordinate progress and address technical challenges. Building on the developments reported in the 10th quarterly report, the team focused efforts on Tasks 2.2, 3.1, 4.1, 4.2, 5.1, and 6 during Quarter 11. The following sections provide detailed summaries of the key activities and accomplishments achieved during this reporting period.

Task 2.2 Develop a recommender engine as a decision support tool for providing goal-oriented mitigation measures and modification/upgrading of repurposed pipelines for hydrogen: During this reporting period, the research team from the University of Texas at Arlington (UTA), including Dr. Zhibin Lin, Dr. Hong Pan, and graduate researcher Mohsin Ali Khan, focused on developing a framework for remaining useful life (RUL) prediction as part of the broader decision support system. Key activities and accomplishments are summarized below:

(1) Development of Risk-Based Ontology: A foundational step was the development of a comprehensive risk-based ontology, which formalizes the structure and semantics of key concepts relevant to pipeline degradation and integrity. As illustrated in Figure 1, the ontology includes nine interconnected classes: PipelineSegment, Corrosion, LeakEvent, Overpressure, MaterialDefect, ExternalLoading, Inspection, RiskAssessment, and Mitigation. These classes are connected via directed relationships such as "caused_by," "influences," "detected_by," and "evaluated_by," capturing complex interdependencies in the integrity assessment process. The ontology aligns with the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) guidelines for Gas Transmission Integrity Management (49 CFR Part 192 Subpart O). These federal regulations mandate that operators implement a systematic process to identify threats, assess risks, and establish mitigation strategies for High Consequence Areas (HCAs). Recognizing the distinct failure mechanisms introduced by hydrogen service, the ontology was extended to incorporate threat identification and assessment

processes from ASME B31.8S. These include hydrogen embrittlement, accelerated fatigue, and new modes of internal corrosion-threats that are not typically dominant in natural gas systems. The resulting ontology serves as a machine-readable knowledge base, bridging traditional integrity management frameworks with emerging hydrogen-specific risk factors.

(2) Spatio-Temporal Knowledge Graph (STKG) Construction: Leveraging the ontology, a Spatio-Temporal Knowledge Graph (STKG) was constructed to model dynamic risk propagation and system-level interactions across pipeline networks. In this graph, each node represents a pipeline segment, event, or inspection outcome, while edges capture causal, spatial, and temporal dependencies. Spatial relationships account for how threats in one pipeline segment may influence adjacent segments, such as through stress redistribution or corrosion under mechanical damage. Temporal relationships track the evolution of threats, inspections, and repairs over time.This graph-based architecture allows the RUL model to go beyond static analysis by incorporating evolving risk contexts, time-dependent degradation trends, and inter-segment dependencies. For example, a corrosion defect detected during a recent inspection may increase the likelihood of failure in an adjacent segment due to environmental coupling or flow-induced stresses. The STKG captures this interaction, enabling context-aware prognostics that are both localized and system-informed.

(3) By embedding expert-curated ontological knowledge into the modeling process, the framework is designed to overcome limitations of purely data-driven models, which often struggle with limited historical hydrogen pipeline data. The ontology-guided STKG enhances interpretability, supports regulatory traceability, and provides an extensible structure for incorporating new threat types as hydrogen standards evolve. Additionally, the framework supports multi-source data fusion, enabling integration of sensor readings, inspection records, material properties, and environmental data. Planned machine learning components will operate on this enriched graph to forecast degradation progression and estimate remaining useful life. This hybrid approach supports not only high-accuracy prediction but also traceable decision support, which is critical for regulatory review and safety assurance.

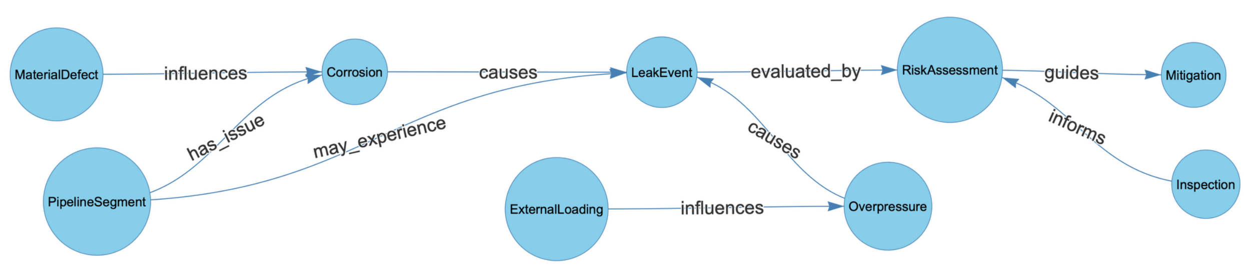

Figure 1. The ontology of the pipeline risk assessment

Task 3.1 Design of near real-world testbed for pipelines transporting pure hydrogen/hydrogen blends to simulate accelerated field conditions in a realistic environment: During this reporting period, the research team, including Mr. J. Anderson from the Energy & Environmental Research Center (EERC), continued the preparation and fabrication of the near real-world hydrogen pipeline testbed. The system is being developed to simulate accelerated field conditions for pipelines transporting pure hydrogen or hydrogen/natural gas blends, while ensuring all necessary safety protocols and operational requirements are met. Progress is summarized in two major categories: (1) current project status and (2) general fabrication and installation plan:

(1) Progress on this project from the EERC for this quarter of reporting is as follows:
- All pipeline components, including pipe sections and flanges, have been delivered and are now on site at the EERC.
- Final checks are underway on the engineering drawings to confirm fabrication specifications before welding begins. Once approved, certified EERC welders will proceed with the pipeline assembly.
- Following the welding stage, the pipeline will be installed in a designated pilot testing area. After placement, the remaining system components—including tubing, valves, regulators, gas booster, and safety accessories—will be integrated.
- Due to scheduling constraints at EERC with multiple ongoing pilot-scale projects, fabrication and installation will occur during the available windows between other system operations. The goal is to complete the system shakedown by August or, at the latest, early September 2025.

(2) The general fabrication plan is the following:
- Final Engineering Approval: Engineering drawings specifying weld procedures and fabrication details are under final review. Upon approval, certified welding will be carried out according to industry-standard pressure codes to ensure the system meets safety and operational pressure thresholds.
- Pipeline Assembly and Mounting: The pipeline will be mounted on custom-built stands or blocks to avoid direct contact with the ground and to maintain structural stability. This mounting approach ensures accessibility and minimizes stress concentrations at the flanges and welded joints.
- System Integration and Piping Installation: Once the pipeline is secured, experienced EERC personnel will begin installing the process tubing, fittings, valves, and instrumentation necessary to create a closed-loop hydrogen flow system. Special attention will be given to the layout in accordance with the finalized Piping and Instrumentation Diagram (P&ID). This ensures all components are correctly located for safe operation and efficient depressurization following each test cycle.
- Leak Testing and Pre-Operational Checks: Before introducing hydrogen or hydrogen blends into the system, the entire pipeline and loop will undergo pressure testing and cycling with nitrogen gas. This step is critical for identifying potential leaks, operational inefficiencies, or design flaws. Any necessary modifications will be made to resolve issues prior to commissioning the system for actual hydrogen testing.

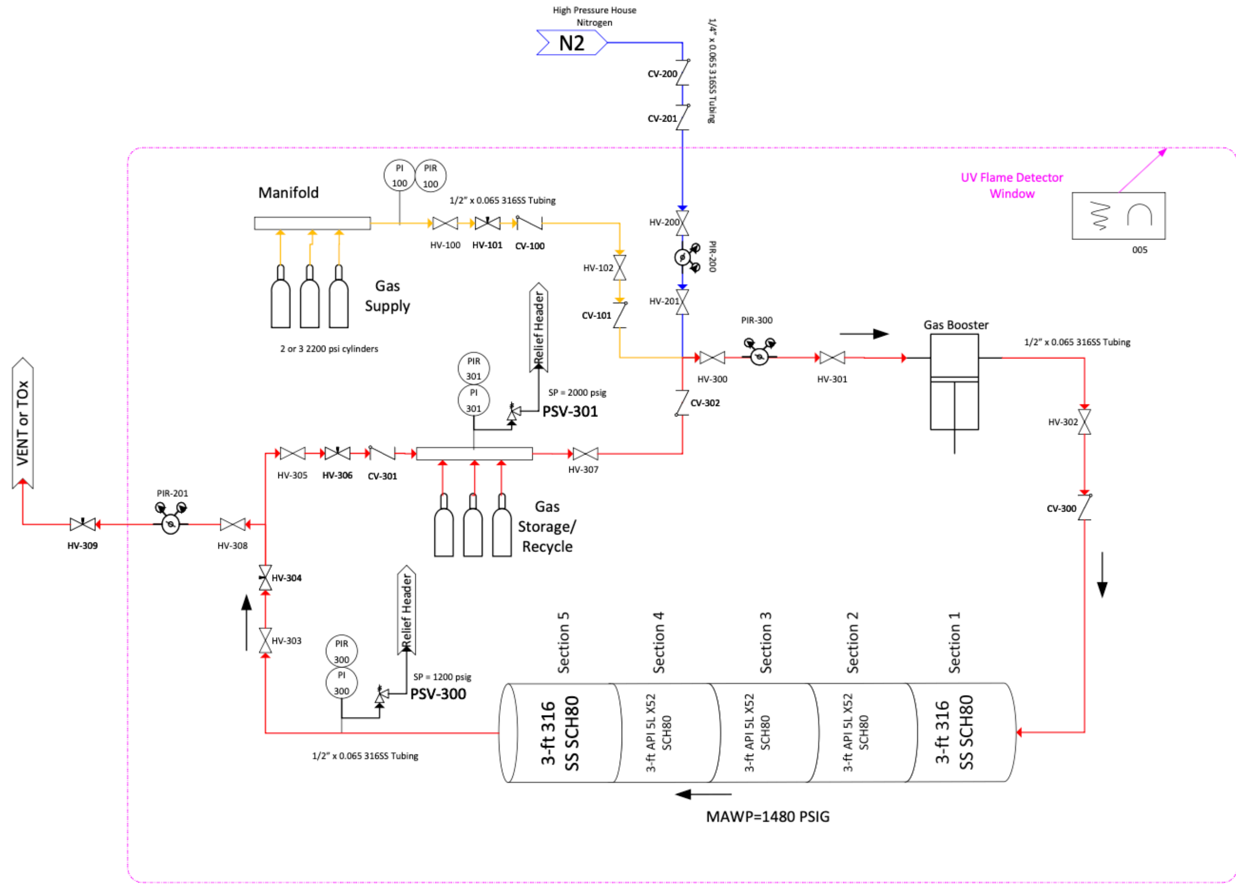

Figure 2. Piping & instrumentation diagram

Task 4.1 Gaining an understanding of long-term hydrogen impacts, & Task 4.2 understanding of hydrogen adsorption and distribution in existing aged pipe materials through macro-scale simulation: During this reporting period, the Virginia Tech team, led by Dr. Kevin Wang, focused on simulating hydrogen absorption behavior and conducting finite element analysis (FEA) to investigate stress distribution in pipeline components. The key activities and progress are summarized as follows:

(1) This report summarizes recent progress on our ongoing project focused on hydrogen absorption modeling and simulation in gas transportation pipelines. Our primary objective is to develop a computational framework that integrates internal fluid dynamics with the adsorption and absorption behavior of hydrogen in pipeline materials. In this reporting period, we have made progress in refining our model and addressing technical questions raised by our sponsor.

(2) We continued the design and implementation of a multiphysics computational model that couples hydrogen gas (or hydrogen – natural gas mixture) dynamics with its interaction with the steel pipeline interior. The model accounts for transient fluid flow, boundary layer behavior near the pipe wall, and the subsequent diffusion and absorption processes within the steel matrix.

(3) In response to the sponsor's valuable feedback, we revisited the assumptions used in defining the hydrogen diffusion coefficient *D* ([length]2/[time]) in pipeline materials

(primarily steel). Recognizing that D can vary significantly based on microscopic defects, residual stresses, and material manufacturing processes, we have begun incorporating a more robust and conservative treatment of diffusion in our simulations. Following on the sponsor's suggestions, we are looking into the following three aspects.

(4) Maximum Allowable Operating Pressure (MAOP): We are examining how operating pressure, specifically at 72% of the Specified Minimum Yield Strength (SMYS) per §192.105, may influence diffusion and embrittlement processes through the generation of stress-induced defects. Pipe Manufacturing Variability: Consideration has been given to material variability across manufacturing eras, particularly between pre-1970 low-frequency Electric Resistance Welded (ERW) pipes and post-1970 steel compositions. Differences in microstructure and defect distributions are being factored into the model's material database. Inline Inspection (ILI) Data: We have initiated a review of ILI data from tool modalities such as Axial and Circumferential Magnetic Flux Leakage (MFL), Shear Wave Ultrasonic Testing (UT), and Electromagnetic Acoustic Transducers (EMAT). These datasets are being used to calibrate spatial variability in pipe wall integrity and to estimate stress concentrations that may affect hydrogen transport.

(5) Our tentative idea is to conduct a parametric study with D varying within a reasonable range while keeping pipe geometry and other parameters unchanged, and to report the dependence of hydrogen embrittlement (and hydrogen-induced damage in general) on diffusivity. The MAOP values will be used to set the mean flow conditions within the pipeline. We will also consider different diffusivity coefficients corresponding to pre-1970 and post-1970 steel materials.

Task 5.1 Gaining an understanding of long-term hydrogen impacts on component-/system-level pipelines, and facilities typically used for gas transmission/distribution lines: During this reporting period, the team (Dr. Zhibin Lin, Dr. Hong Pan and Mohsin Ali Khan, UTA) is focus on embedding the modified Paris' law crack growth estimator as an explicit feature in our deep learning RUL model and do an sensitive analysis activities include:

1) Compute cycle-by-cycle Paris'-law crack growth estimates (N_{phys}) by numerical integration of $\frac{da}{dN} = C_{H2}\,(P,\,R,\,f,\,q) \cdot (\Delta K)^m$ from an assumed initial flaw size a_0 to critical crack length a_{crit}.
2) Fuse these physics-based life estimates with sensor-derived features into the ML training dataset.
3) Retrain the existing neural RUL predictor with the new physics-informed feature.
4) Perform sensitivity sweeps over hydrogen-environment parameters $(C,\,m,\,q)$ to assess robustness of the hybrid predictor under model-form uncertainty.

This and following up works will establish the groundwork for a truly hybrid physics–ML RUL framework, improving both interpretability and reliability of life-prediction under hydrogen-assisted cracking conditions.

Task 6 Summarize the guidelines/best practices summarization: The research team, including Dr. Zhibin Lin, Dr. Hong Pan, and Mohsin Ali Khan from the University of Texas at Arlington (UTA) summarize and elucidate best practices and guidelines from different perspective, further improve the completeness of the best practice recommendation. Their findings are summarized as follows:

Category	Best Practices
Integrity Assessment & Material Compatibility	• Evaluate pipeline age, wall thickness, welding and defect history • Test steel for hydrogen embrittlement and fatigue crack-growth susceptibility • Assess polymeric components (valves, seals) for permeability and long-term performance in H_2 service
Standards & Regulatory Compliance	• Follow ASME B31.12 for new hydrogen lines • Apply the ASME B31.8 hydrogen exception chapter for repurposed pipelines • Reference ISO and NFPA hydrogen codes for design, inspection, and safety
Operational Modifications	• De-rate operating pressures to mitigate embrittlement risks • Retrofit or replace compressors and impellers for H_2 compatibility • Adjust flow management to account for hydrogen's low density and viscosity
Leak Detection & Safety Protocols	• Deploy hydrogen-sensitive leak detection sensors • Increase inspection frequency using ultrasonic and inline inspection tools • Reclassify compressor and metering stations under NFPA hydrogen safety standards
Pilot Projects & Validation	• Conduct controlled blending trials (e.g., HyDeploy up to 20 % H_2) • Use full-scale loop tests (e.g., HyNTS) to study material aging and cyclic effects
Techno-Economic & Environmental Analysis	• Employ models such as NREL's HyBlend and BlendPATH for cost/emissions scenarios • Perform site-specific life-cycle assessments of CAPEX, compression energy, and CO_2 savings • Incorporate local factors: pipeline topology, demand patterns, and regulations
Monitoring & Maintenance	• Schedule frequent integrity inspections (UT, ILI) tailored to hydrogen-induced damage • Update cathodic protection and use H_2-compatible lubricants and seals • Implement seal and joint monitoring to detect increased leak rates
Stakeholder Engagement & Regulatory Adaptation	• Engage regulators and end-users early on blend limits and emergency response plans • Phase hydrogen concentration increases based on pilot outcomes • Align policy frameworks to support repurposing and blended-gas approvals

Project Financial Activities Incurred during the Reporting Period:

The cost breakdown for each budget category during the reporting period is presented in Table 2. Please note that expenses, particularly those from subcontracted Co-PIs, may be delayed due to processing times between institutions.

Table 2 Cost breakdown during the reporting period (Q11)

Category	Amount spent during Q11
Personnel	
Faculty	$0.00
Postdoc	$0.00
Students (RA and UR)	$0.00
Benefits	$0.00
Operating Expenses	
Travel	$0.00
Materials and Supplies	$0.00
Recharge Center Fee	$0.00
Consultant Fee	$0.00
Subcontracts	$74,163.22
Indirect Costs	$0.00

Project Activities with Cost Share Partners:

A 12-month no-cost extension has been applied; Virginia Tech has fulfilled all of its cost share commitments, and the remaining cost share will be provided by NDSU faculty members and tuition waivers for Ph.D. research assistants during the extension period.

Project Activities with External Partners:

During this reporting period, the research team meets regularly bi-weekly, and the sub-universities have researched as planned.

Potential Project Risks:

No potential risks were noticed during this reporting period.

Future Project Work:

During the upcoming quarter, the research team will continue work on Tasks 2.2, 3.1, 4.1, 5.1, and 6.1, with particular emphasis on accelerating progress in Task 3.1.

Potential Impacts on Pipeline Safety:

A framework for remaining useful life (RUL) prediction has been developed as part of the broader decision support system. In parallel, deep learning models demonstrate strong potential for accurately forecasting system degradation. For the hydrogen flow testing facility, engineering drawings specifying weld procedures and fabrication details are currently under development. Additionally, hydrogen absorption simulation results provide a solid foundation for future safety-related studies by offering critical insights into material behavior under hydrogen exposure. By integrating simulation data, machine learning predictions, and experimental validation, this comprehensive approach supports enhanced predictive maintenance and improves the safety and reliability of hydrogen pipeline infrastructure.