

CAAP Quarterly Report

10/07/2025

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: 06/28/2025 – 09/27/2025

Project Activities for Reporting Period:

In this quarterly report (Q12), the research teams continued to hold regular biweekly meetings to coordinate project progress, address technical challenges, and align ongoing tasks. Building upon the developments presented in the 11th quarterly report, focused efforts during Quarter 12 were directed toward Tasks 2, 3, 4, 5, and 6. The following sections summarize the major activities, findings, 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: In the previous reporting period, efforts focused on establishing the remaining useful life (RUL) prediction framework as a foundational component of the overall decision-support system. During this quarter, the UTA team, led by including Dr. Zhibin Lin, Dr. Hong Pan, and graduate researcher Mohsin Ali Khan, made significant progress in developing a decision engine that integrates a domain-specific knowledge graph with a large language model (LLM) for intelligent reasoning and recommendation generation:

- (1) The team advanced the development of a decision-support engine that integrates a domain-specific knowledge graph with a large language model (LLM)-based reasoning layer to identify effective mitigation strategies for retrofitting or upgrading existing pipelines for service with pure hydrogen or hydrogen–natural gas blends. The system curates and organizes mitigation-related entities; including potential threats, pipeline material and design attributes, mitigation and repair methods, and operating conditions; into a structured semantic knowledge graph. The graph encodes probabilistic and causal relationships among these entities, allowing for context-aware reasoning. The LLM interacts dynamically with this graph to query, infer, and rank candidate mitigation measures, evaluate trade-offs between performance and feasibility, and trace evidence pathways supporting each recommendation. This fusion of structured domain knowledge with adaptive LLM reasoning enables data-informed and transparent decision-making,

providing engineers with customized mitigation strategies tailored to specific pipeline configurations, materials, and operating environments.

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: In the previous reporting period, the team continued developing a test system designed to replicate accelerated field conditions for pipelines transporting pure hydrogen and hydrogen–natural gas blends. During the current period, the research team, led by Mr. J. Anderson from the Energy & Environmental Research Center (EERC), finalized the Pipeline Process and Instrumentation Diagram (P&ID) and established an internal Management of Change (MoC) protocol to oversee and document any future modifications to the system design:

- (1) The defined and initiated the fabrication sequence for the near real-world hydrogen test stand: (1) installing the cylinder rack/stand and manifold for initial pipeline fill; (2) mounting the gas booster pump on a dedicated bracket/stand; (3) placing the storage-cylinder rack/stand for pressure-cycling operations after the initial fill; and (4) setting flange supports/stands to secure the pipeline off the ground. Following these permanent placements, the process tubing, instrumentation, valves, and auxiliary equipment are being added in accordance with the P&ID flow path and callouts (Figure 1).
- (2) In addition, a preliminary 3D model is being developed to provide a clear visualization of the test stand layout within the available space, complementing the P&ID for planning and stakeholder review. The team is also refining specifications for a right-sized gas booster compatible with the planned gas composition to mitigate over-pressurization risk and enhance operational safety. These efforts, together with the MoC process and staged fabrication plan, advance readiness for safe and compliant hydrogen testing.

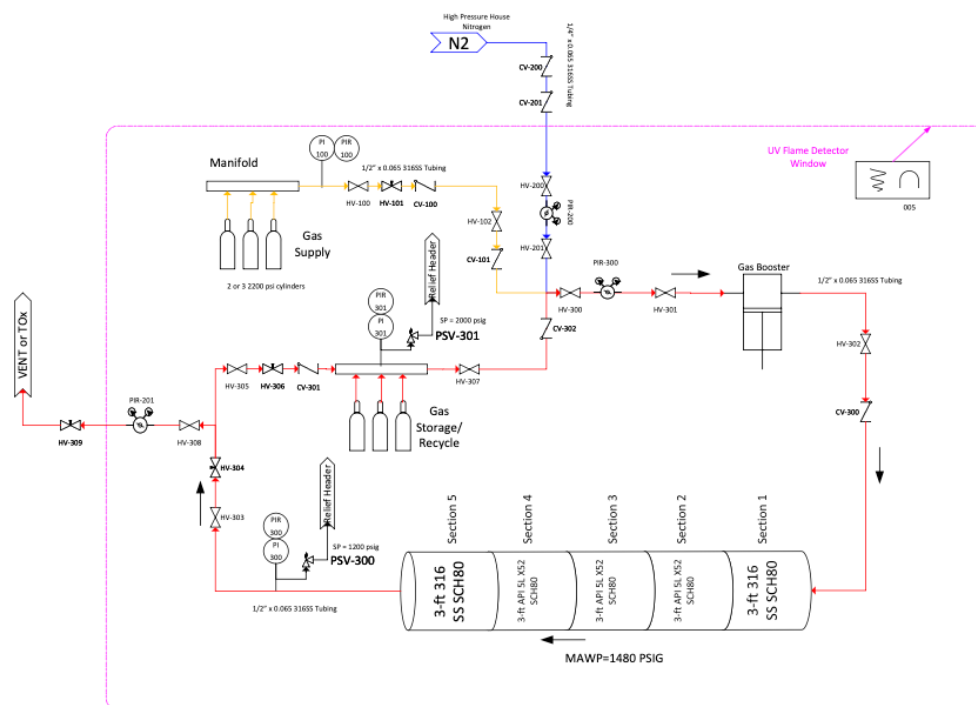


Figure 1. Final design for the pipeline.

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: In the previous reporting period, the team focused on simulating hydrogen absorption behavior and performing finite element analysis (FEA) to examine stress distribution in representative pipeline components. During the current reporting period, the Virginia Tech team, led by Dr. Kevin Wang, advanced efforts using the Multiphysics-based simulation platform M2C, which enables coupled modeling of fluid and structural dynamics under extreme pressure and temperature environments. Key activities and progress achieved during this period are summarized below:

- (1) First, the team has published an open-source Multiphysics-based software package, M2C, that is feasible for simulating fluid and structure dynamics in extreme environments. The solver advances the precision of simulations involving compressible, multi-material flows and two-way fluid–structure interactions by combining a finite-volume compressible Navier–Stokes core with sharp-interface tracking (level set and embedded boundary methods) and exact multi-material Riemann solvers (FIVER). M2C supports arbitrary convex equations of state (e.g., NASG, JWL, Mie–Grüneisen, Tillotson, ANEOS), and adds multiphysics modules for laser radiation/absorption, phase transition via a latent-heat reservoir, and plasma ionization via generalized Saha equations. Implemented in C++ with MPI for high-performance computing and distributed with example cases, M2C has been verified on benchmark Riemann problems and interface-evolution tests and demonstrated on applications including laser-induced cavitation, explosion/blast mitigation, and hypervelocity impact. The successful validation and public release of this solver establish a reliable foundation for future hydrogen-related flow and FSI studies.
- (2) The developed software package can be found at the link (<https://github.com/kevinwgy/m2c#>); and Figure 2 is a screenshot of the page. This developed software package focuses on simulating multi-material fluid flow and fluid–structure interactions (FSI) under extreme conditions involving high pressure, velocity, and temperature. In such environments, material compressibility and thermodynamics dominate the response, leading to shock waves, large deformations, and time-dependent interfaces between materials that must be determined during the analysis. Across these interfaces, variables such as density may change abruptly, while others like velocity remain continuous. The system may also involve external energy input (e.g., lasers) and physical processes such as vaporization or ionization. The M2C framework employs a 3D finite volume solver for compressible flow and supports multiple equations of state, including Noble–Abel stiffened gas, JWL, Mie–Grüneisen, Tillotson, and ANEOS, enabling analysis across various materials. Level set methods capture evolving material interfaces, while an embedded boundary scheme handles fluid–structure coupling and large structural deformations. To compute fluxes across discontinuous regions, M2C uses the FIVER method, ensuring stability under sharp property jumps. M2C operates with a partitioned coupling approach for two-way data exchange with structural solvers, such as Aero-S, and includes modules for latent heat vaporization and Saha-based ionization. The code is MPI-parallelized and built with modular, object-oriented design for scalability and future extension.

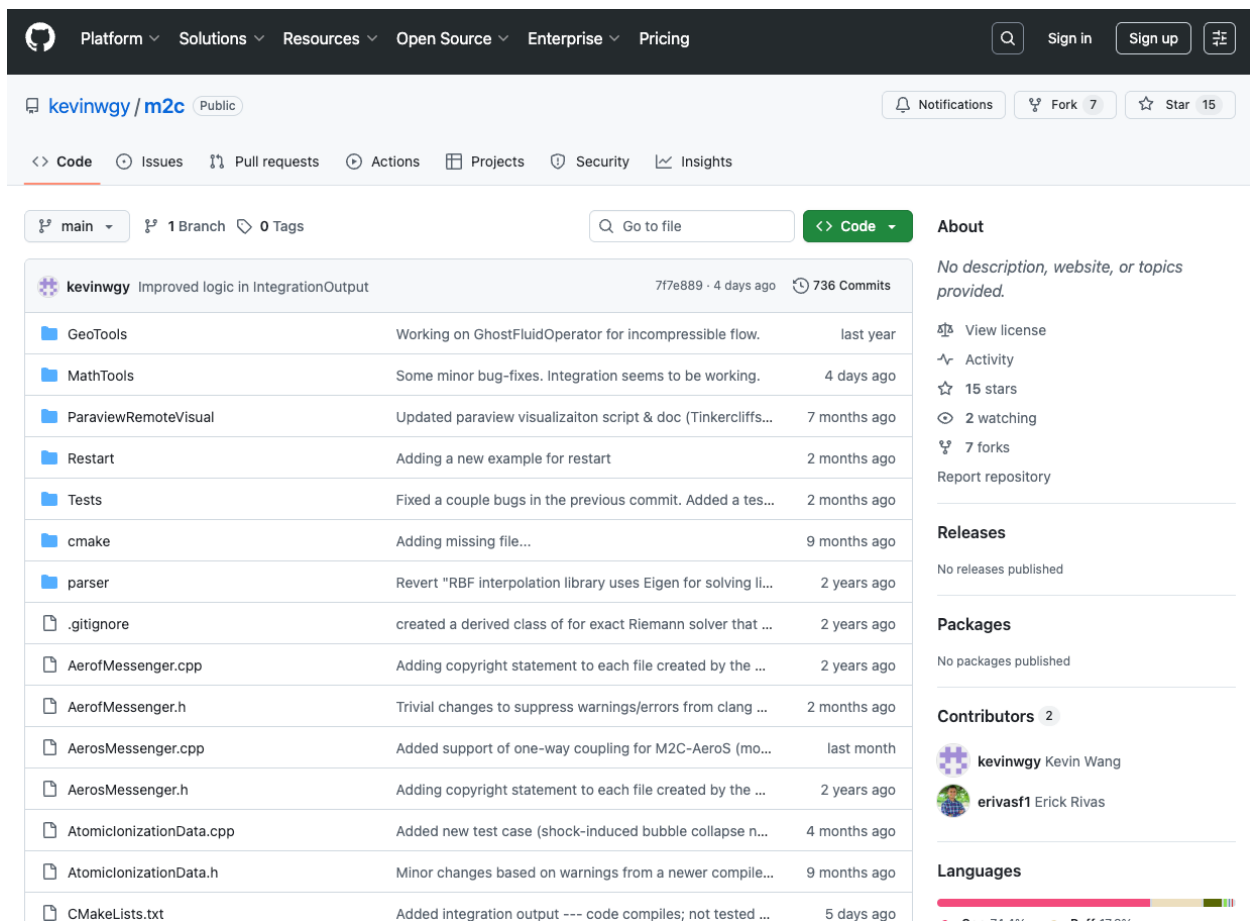


Figure 2. Screenshot of the developed software package.

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: In the previous reporting period, the team integrated a modified Paris' law crack growth estimator as an explicit feature within the deep learning-based remaining useful life (RUL) model. During the current period, the UTA team (Dr. Zhibin Lin, Dr. Hong Pan, and Mohsin Ali Khan) focused on developing a comprehensive cross-scale evaluation framework to assess the impacts of hydrogen and hydrogen-natural gas blends on both component-level behavior and system-level reliability of pipeline infrastructure:

- (1) A comprehensive cross-scale evaluation framework is established to quantify the effects of hydrogen and hydrogen-natural gas blends on both component and system-level performance. This framework ensures consistent linkage between experimental testing, data analytics, and predictive modeling across institutions.
- (2) The team prioritized key pipeline and system components, including pipe segments, girth welds, flanges, valves, seals, fittings, and regulators, and reached consensus on critical impact metrics. These metrics include permeation and leakage rates, embrittlement and ductility indices, crack initiation and propagation tendencies, fatigue

life under pressure cycling, sealing and torque retention, and overall system reliability and availability under hydrogen exposure.

- (3) A phased test matrix was drafted to define test conditions covering a range of hydrogen blend fractions, pressure and temperature levels, and cyclic loading counts representative of real-world pipeline operation. The team also conducted baseline (inert gas) shakedown tests to validate instrumentation accuracy and stability before introducing hydrogen into the system.
- (4) Core instrumentation and sensing components were selected for the test stand, including pressure and temperature transducers, mass-flow meters, hydrogen leak detectors, strain gauges, and acoustic-emission sensors positioned at critical joints. A standardized data schema was defined, incorporating precise timestamping, synchronization, and quality-assurance protocols to ensure consistent and repeatable comparisons across multiple test runs.
- (5) Analysis and Modeling Integration: The team developed preliminary performance-limit criteria, including leak tightness thresholds, allowable strain levels, and cycle-to-failure definitions. A reliability model was initiated using a fault-tree and Bayesian-network framework, informed by the knowledge-graph relationships established in Task 2.2. This model is being structured to assimilate data from the test stand in real time, continuously updating both component- and system-level risk assessments.
- (6) Collectively, these efforts lay the groundwork for the upcoming phase of controlled hydrogen and blend cycling tests on fully instrumented components. The forthcoming data will enable direct correlation between measured degradation signatures and system-level mitigation strategies, ultimately supporting the development of quantitative guidelines for hydrogen-compatible infrastructure.

Task 6: Summarize the guidelines/best practices. The research team, including Dr. Zhibin Lin, Dr. Hong Pan, and Mohsin Ali Khan from the University of Texas at Arlington (UTA), worked on compiling and refining best practices and guidelines from multiple perspectives to enhance the completeness and applicability of the overall recommendations. Their key findings and updates are summarized as follows:

- (1) A best-practice framework for safely blending hydrogen into existing natural-gas networks was synthesized, emphasizing North American conditions and practical near-term ranges of ~5–20% H₂ by volume ($\leq 5\%$ for sensitive systems, up to 20% where materials, appliances, and operations are validated), covering: a) readiness assessment—material inventory (steel grades/ages, plastics/elastomers), baseline integrity (ILI/hydrotest), hydrogen-capable leak detection, targeted lab tests for vintage/high-strength steels, and checks on valves, regulators, meters, and odorization; b) blend limits and operations—a phased ramp (1–2% $\rightarrow$ 5–10% $\rightarrow$ $\leq 20\%$) with hold-point KPIs, pressure/flow management and stress derating where required, and gas-quality governance at interconnections; c) end-use preparedness—bench-testing representative appliances, managing sensitive users (e.g., turbines/CNG) via isolation/retrofit/cleanup, and clear customer communication; and d) monitoring, integrity, and compliance—enhanced LDR, shortened inspection intervals for steel transmission, instrumentation of fatigue-critical locations, a data/forensics loop with coupons to refine limits, project-specific safety cases/MoC, alignment with hydrogen pipeline and appliance standards (“H₂-ready”), transparent tariff/blend disclosures, and

verification of low-carbon H₂ for demonstrable CO₂ reduction; deliverables include a Best-Practice Playbook, a decision-tree for progressing from ≤5% to ≤20% blends, and a template safety/monitoring plan, with next steps to validate on representative segments (steel vs. PE) and encode these rules into the Task 2.2 knowledge-graph/LLM engine for segment-specific recommendations.

- (2) To ensure the safe and effective blending of hydrogen into existing natural gas networks, particularly in North America, pipeline operators, research institutions, and regulatory agencies are jointly developing best practice frameworks. These frameworks provide step-by-step technical guidance to evaluate feasibility, infrastructure readiness, and operational safety when introducing hydrogen. They emphasize risk assessment, material compatibility, leak detection, and continuous monitoring to maintain safe and reliable operation. The proposed workflow outlines a clear sequence of actions for different hydrogen blend levels, specifying what must be evaluated, modified, or verified during system transition. Each step is grounded in the scientific understanding of hydrogen behavior in pipelines, including diffusion, embrittlement, and sealing performance. A detailed illustration of this best practice flow is presented in Figure 3, summarizing the key decision points and validation steps in the blending process.

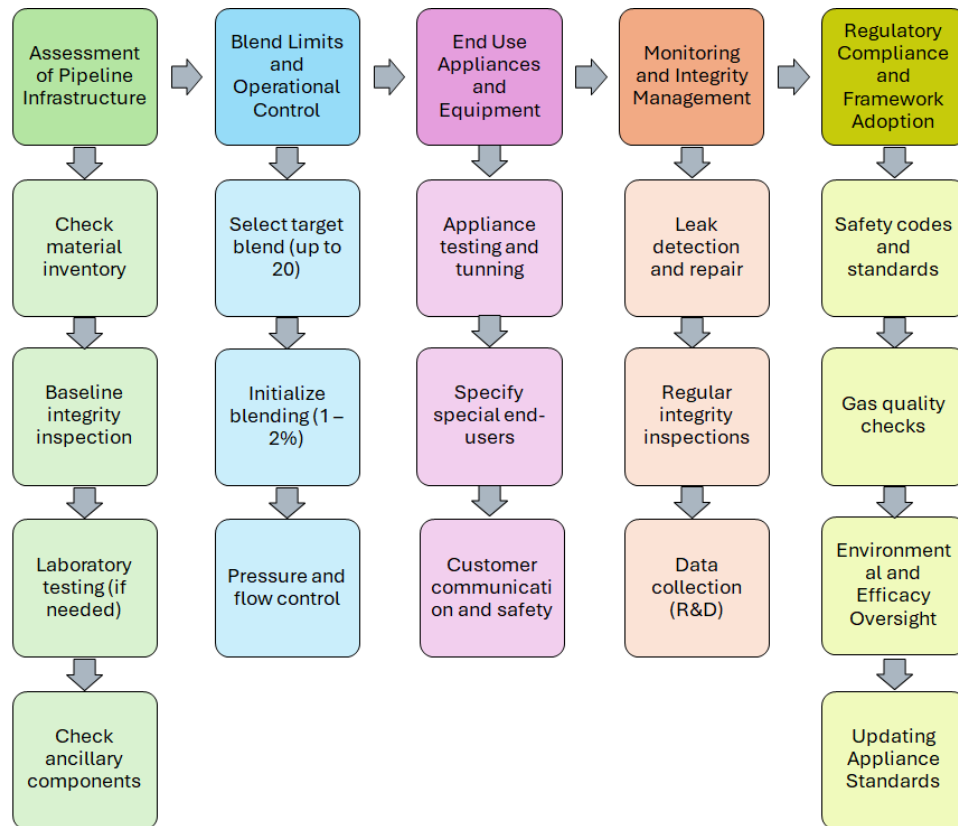


Figure 3. The stages involved in implementing best practices for hydrogen blending.

Project Financial Activities Incurred during the Reporting Period:

The cost breakdown for each budget category during the reporting period is presented in Table 1.

Table 1. Cost breakdown during the reporting period (Q12).

Category	Amount spent during Q12
Personnel	
Faculty	\$0.00
Postdoc	\$2,341.67
Students (RA and UR)	\$800.00
Benefits	\$1,331.14
Operating Expenses	
Travel	\$0.00
Materials and Supplies	\$0.00
Recharge Center Fee	\$0.00
Consultant Fee	\$0.00
Subcontracts	\$105,817.05
Indirect Costs	\$0.00

Project Activities with Cost Share Partners:

A 12-month no-cost extension has been approved through August 2025. Virginia Tech has completed all of its cost-share commitments, and the remaining cost share will be provided by NDSU faculty contributions and tuition waivers for Ph.D. research assistants.

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 next reporting period, the research team will continue advancing Tasks 2, 3, 4, 5, and 6, with particular emphasis on expediting progress in Task 3.

Potential Impacts on Pipeline Safety:

During this quarter, an advanced decision engine was developed that integrates a domain-specific knowledge graph with a large language model (LLM) to support intelligent reasoning and mitigation planning. This establishes the foundation for upcoming hydrogen and blend cycling tests on instrumented components and the translation of degradation data into system-level mitigation strategies. By combining simulation results, machine learning predictions, and experimental validation, this framework enables data-driven maintenance and improves the safety and reliability of hydrogen pipeline infrastructure.