CAAP Quarterly Report

12/27/2024

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: 09/28/2024 – 12/27/2024

Project Activities for Reporting Period:

In the quarterly report, the teams have undergone a Principal Investigator (PI) change process, and subcontracts have been renewed. Additionally, we organized and conducted a mid-term meeting with PHMSA. Building on the previous annual report, the research team focused on tasks 2.2, 3.1, 4.1, 5.1, and 6.1 during this quarter (Quarter 9). The following sections provide detailed summaries of the major activities completed during this reporting period.

Task 2.2, Conducting data preprocessing based on the elbow point: During this reporting period, the research team, consisting of Dr. Zhibin Lin, Dr. Hong Pan, and Mohsin Ali Khan (UTA/NDSU), carried out the data preprocessing necessary for detecting functional failures in the pipeline. A summary of the key activities and findings is provided below:

1) Elbow Point Detection
Degradation becomes more marked after the “elbow point”, which corresponds to the start of functional failure. Any signal representing system behavior can generally be divided into two portions i.e., a linear portion, followed by an exponential part. The exponential part shows the more severe stage of degradation. By aiming solely at the exponential part i.e., the post-elbow point and disregarding the linear portion before it, more accurate Remaining Useful Life (RUL) estimates can be attained. Baptista et al. demonstrated that the significantly improved prognostic and RUL estimation, considering the detection of elbow point in the degradation pattern using recurrent neural network (RNN), which eventually validates the prominence of the exponential degradation stage over the initial linear phase.

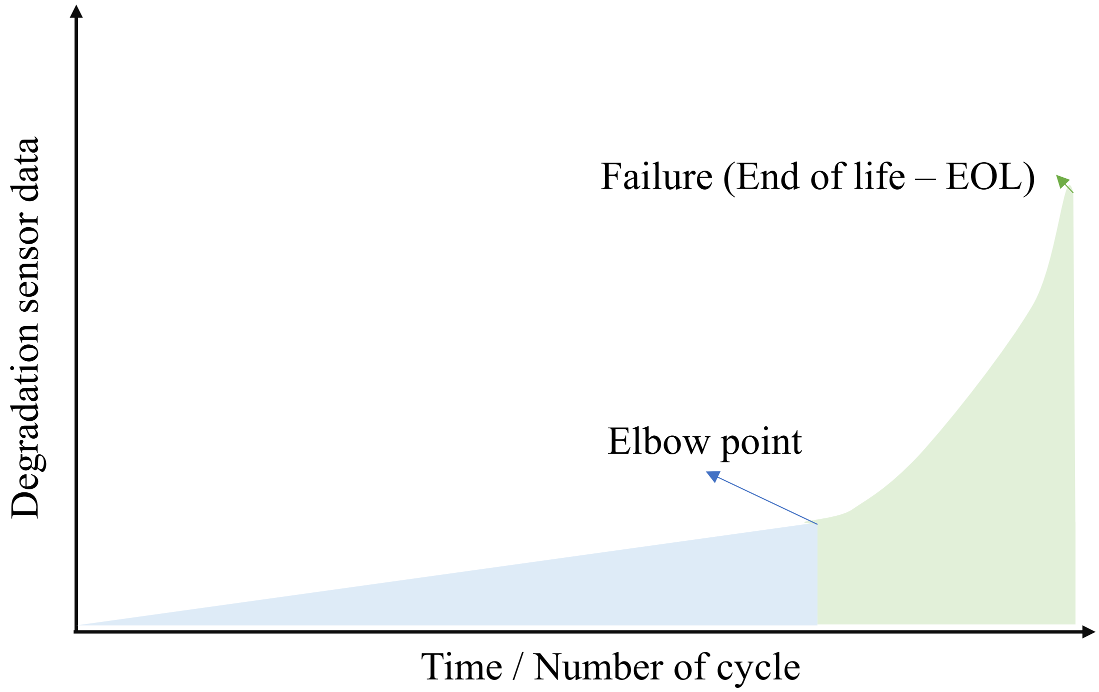


Figure 1. The elbow point in the generated degradation signals differentiates between the linear portion and exponential growth phase.

Task 3.1, Preparing the near real-world testbed for hydrogen testing: During this reporting period, the research team, including Mr. J. Anderson from EERC, encountered a subcontract suspension, which delayed the testing process. Despite this setback, the team continued to work on the facility setup to ensure progress.

Task 4.1, Gaining an understanding of long-term hydrogen impacts: During this reporting period, the Virginia Tech team, led by Dr. K. Wang, focused on two key tasks: verifying incompressible fluid dynamics and reviewing the literature on modeling hydrogen transport in unsteady, low-speed fluid flows. These efforts are summarized as follows:

1) Verification of the incompressible fluid dynamics solver developed recently. The main concepts of this solver are described in the last report, also see Figure 2. In this reporting period, we have designed several model problems in which the size and shape of the pipe defects are varied.

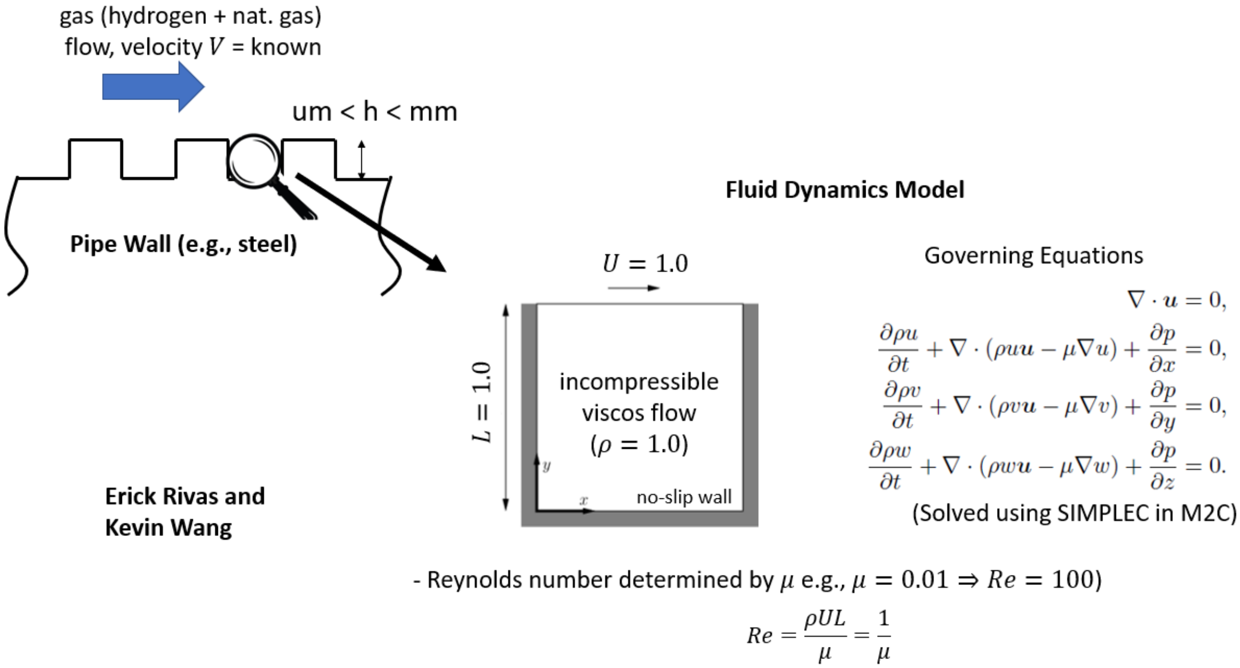
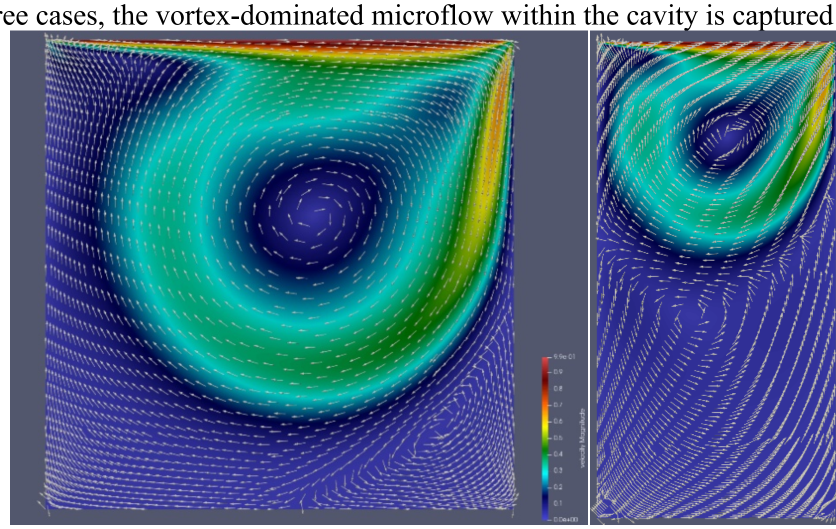


Figure 2. Development of the model problem and a benchmark test case.

Figure 3 shows some example results. In these figures, the Reynolds number of the flow is fixed to 1000. The aspect ratio of defect (assumed to be a rectangular cavity) varies between 0.5, 1.0, and 2.0. In all three cases, the vortex-dominated microflow within the cavity is captured clearly.



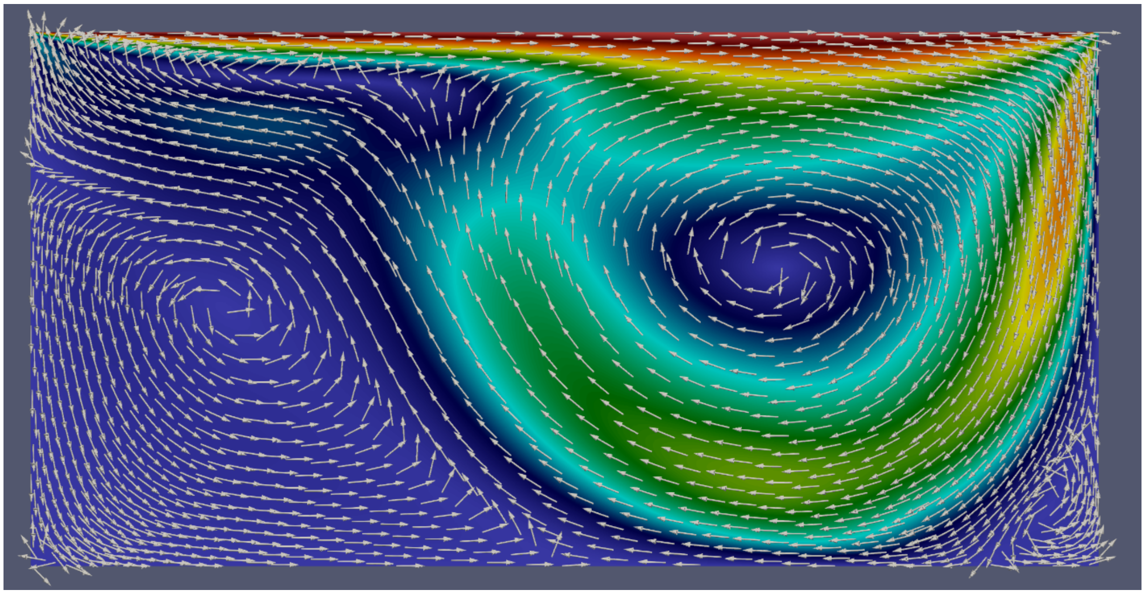


Figure 3. Simulation results of flow within a cavity, obtained using research code M2C with cavity aspect ratio 0.5, 1.0, and 2.0. (See Figure 1 for the model setup)

2) Review of literature on modeling hydrogen transport within unsteady low-speed fluid flows. Hydrogen transportation pipelines may carry not only pure hydrogen gas but also mixtures of hydrogen, air, and other impurities. Each component in the mixture has a different diffusion coefficient, which necessitates accounting for the concentration and diffusion effects of hydrogen when modeling hydrogen-induced material damage.

Our literature review reveals that the state-of-the-art approach for modeling gas mixtures in computational fluid dynamics (CFD) involves extending the conventional Navier-Stokes equations with transport equations for each gas species to be tracked. Each transport equation is assigned a specific diffusion coefficient, allowing the coupled system to separately track the transport of different species (hydrogen, air, and impurities).

This methodology can be implemented using commercial CFD software such as Ansys Fluent. Additionally, incorporating this feature into our research code is straightforward.

Task 5.1, Analyzing impacts on component- and system-level pipelines: During this quarter, the research team, including Dr. Zhibin Lin and Dr. Hong Pan from UTA, and Mohsin Ali Khan from NDSU, continued their research on failure assessment diagrams (FAD). Their findings are summarized as follows:

To optimize the use of the Failure Assessment Diagram (FAD) in bridging component-level failures to system-level failures, we have conducted a comprehensive literature review. This review highlights the advantages and disadvantages of using the FAD for pipeline applications.

Table 1: The advantages and disadvantages of FAD in pipeline failure assessment.

FAD property	Advantages	Disadvantages
Comprehensive Analysis	Integrates material properties, loading conditions, and flaw sizes to assess failure risks effectively.	May not fully capture complex loading conditions, such as dynamic or transient loads.

Comprehensive Analysis	Accounts for both brittle fracture and plastic collapse, enabling a holistic evaluation.	Assumes idealized material behavior, which might not reflect real-world imperfections.
Scalability	Applicable to both component and system levels, bridging individual and system-wide insights.	Complexity increases for system-level assessments, requiring advanced computational tools.
Simplified Decision-Making	Visual representation aids in determining safe operating conditions versus failure risks.	Static assessments require periodic updates to reflect changing pipeline conditions.
Standards and Guidelines	Recognized in industry standards, ensuring regulatory compliance.	Requires adaptation for advanced or novel materials, such as hydrogen-affected pipelines.
Predictive Capability	Identifies critical areas prone to failure, aiding in proactive maintenance planning.	Not suitable for real-time monitoring; assessments are based on pre-collected data.
Data Requirements	-	Highly dependent on accurate and detailed input data (material properties, crack dimensions, etc.).
Material Limitations	-	May not be directly applicable to advanced materials without additional calibration or validation.

Task 6.1, Propose guidelines/best practices: During this quarter, the research team, including Dr. Zhibin Lin and Dr. Hong Pan from UTA, and Mohsin Ali Khan from NDSU, Summarized the best practice for repurposing the existing pipeline for hydrogen transportation. Their findings are summarized as follows:

Transitioning existing pipelines for hydrogen or blended transport requires addressing unique challenges, including material compatibility, pipeline integrity, and safety risks. Following a comprehensive review, we have summarized key practices, such as material assessments, operational modifications, and regulatory compliance, to ensure a safe, reliable, and cost-effective transition, as outlined in Table 2.

Table 2: The best practice for repurposing existing pipeline from different methods.

Methods Category	Best Practice
Material Assessment	Evaluate Material Compatibility: Assess the pipeline material's resistance to hydrogen-induced degradation.
	Conduct Fracture Toughness Testing: Ensure materials can withstand hydrogen exposure under operational pressures.
Pipeline Integrity Assessment	Perform Baseline Inspections: Use advanced NDE techniques to identify existing flaws or vulnerabilities.
	Develop a Risk-Based Inspection (RBI) Program: Focus on high-risk areas such as welds, joints, and high-stress zones.
	Assess Remaining Life: Determine the pipeline's fatigue life under hydrogen service conditions.

Design and Operational Modifications	Lower Operating Pressures: Reduce pressure to minimize risks of hydrogen embrittlement and leaks.
	Control Flow Rates: Optimize flow rates to prevent turbulent or high-velocity flow, which could exacerbate stress.
	Install Monitoring Equipment: Use real-time sensors for detecting leaks, pressure changes, and other critical parameters.
Blending Strategies	Define Hydrogen Blending Ratios: Limit hydrogen content to levels the materials can tolerate (commonly <20%).
	Establish Mixing Protocols: Ensure proper blending to avoid stratification or uneven hydrogen distribution.
Coating and Cathodic Protection	Inspect and Upgrade Coatings: Verify that pipeline coatings are resistant to hydrogen and mitigate corrosion risks.
	Enhance Cathodic Protection: Adjust protection systems to account for electrochemical behavior changes due to hydrogen.
Safety Measures	Leak Detection Systems: Implement advanced hydrogen-specific leak detection technologies.
	Emergency Response Plan: Develop and train personnel on hydrogen-specific emergency response protocols.
	Regular Training: Train operators and maintenance teams on the unique challenges of hydrogen transport.
Regulatory and Compliance	Adhere to Standards: Follow industry standards such as ASME B31.12 for hydrogen pipelines and related codes.
	Engage Regulators Early: Collaborate with regulatory bodies to ensure compliance and streamline approvals.
Knowledge Integration	Leverage Data-Driven Models: Use computational tools like knowledge graphs and ML for predictive maintenance.
	Collaborate Across Disciplines: Integrate expertise for a holistic approach to pipeline transition.
Pilot Testing and Phased Implementation	Run Pilot Tests: Conduct small-scale trials to validate pipeline performance under hydrogen conditions.
	Adopt a Phased Approach: Gradually transition pipelines to full hydrogen service starting with low hydrogen percentages.

Project Financial Activities Incurred during the Reporting Period:

The cost breakdown for each category during the reporting period, as outlined in the budget proposal, is presented in Table 3. Due to the ongoing contract amendment related to the PI change and subawards, the costs have been impacted, and there have been no significant expenses during this quarter (Q9).

Table 3. Cost breakdown during the reporting period (Q9).

Category	Amount spent during Q9
Personnel	
Faculty	$0
Postdoc	$0
Students (RA and UR)	$0
Benefits	$0
Operating Expenses	
Travel	$0

Materials and Supplies	$0
Recharge Center Fee	$0
Consultant Fee	$0
Subcontracts	Subawards issued
Indirect Costs	$0

Project Activities with Cost Share Partners:

As previously mentioned, there has been no significant expense due to the subcontract suspension; therefore, the matching funds have also been paused. Once the contract is finalized, the matching funds will primarily come from RA tuition waivers for those who continue working on this project.

Project Activities with External Partners:

During this reporting period, the research team held regular bi-weekly meetings, and the sub-universities conducted their research activities as scheduled. Additionally, the research team presented the project's progress during the mid-term meeting with PHMSA on December 3, 2024.

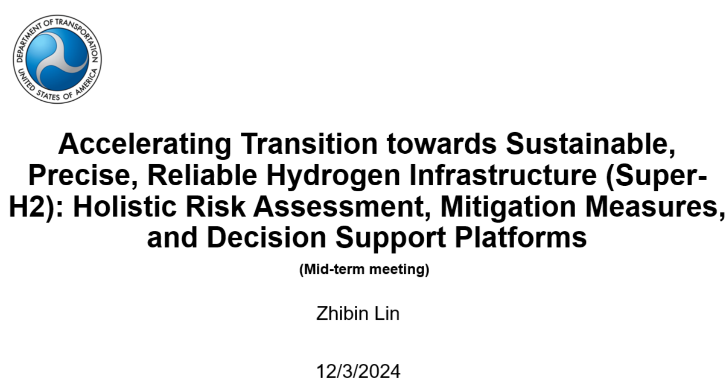


Figure. 4 The Mid-term meeting.

Potential Project Risks:

No potential risks were noticed during this reporting period.

Future Project Work:

During the upcoming quarter, the research team will persist in their efforts on Tasks 2.2, 3.1, 4.1, 5.1, and 6.1, with a specific emphasis on accelerating task 3.1 for near real-world testbed.

Potential Impacts on Pipeline Safety:

The simulation result can be a basis for further safety-related hydrogen simulations.