CAAP Quarterly Report

6/30/2024

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

Prepared By: Zhibin Lin (PI), Kevin Wang, Jace Anderson, Hong Pan, Mohsin Ali Khan, and Xuanyu Zhou

Contact Information: Zhibin Lin, Email: zhibin.lin@ndsu.edu, Phone: 701.231.7204

Reporting Period: 4/01/2023 – 6/30/2024

Project Activities for Reporting Period:

In the previous report (Q1-Q6), Task 1, and Task 2.1 were completed, Task 2.2 has set up the main framework, waiting for the following simulation, empirical result to validation, and Task 3.1, 4.1, and 5.1 have finished further analysis. In this quarter (Quarter 7), the research team has worked on Tasks 3.1, 4.1, 5.1 and 6.1. The summaries for the major activities that were completed during this reporting period are detailed below:

Task 3.1 During this reporting period, the research team, led by Mr. J. Anderson from EERC, made progress in preparing the near real-world testbed for hydrogen testing. Specifically, key equipment and space required for the testing setup have been successfully established, and more safety-related conditions are being checked. Below is a summary of the progress made by EERC during this reporting period:

1) The EERC has gotten a quote from STEFFES for the procurement and specific welding of the pipeline. We are currently working with UND procurement to go through the proper procedures for ordering a work order and expected to be processed and sent to STEFFES in early July.
2) Instead of introducing natural gas and hydrogen to an accumulator and testing for blend percentage, it has been decided that the EERC will purchase a pre-blended K-bottle from a distributor like Airgas or a similar gas company. If for some reason Airgas is unable to do that, we will go back to the original plan of mixing the two in an accumulator vessel.
3) Due to the nature of the EERC, there have been multiple projects in the space where the pipeline will be fabricated, so any initial setup of secondary/process tubing and lines has been delayed until the pilot area has a break between runs.

Task 4.1 Gaining an understanding of long-term hydrogen impacts: In the reporting period, the Virginia Tech team (Dr. K. Wang) has developed and validated an incompressible fluid dynamics solver and reviewed the hydrogen transport computational model as summarized below:

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

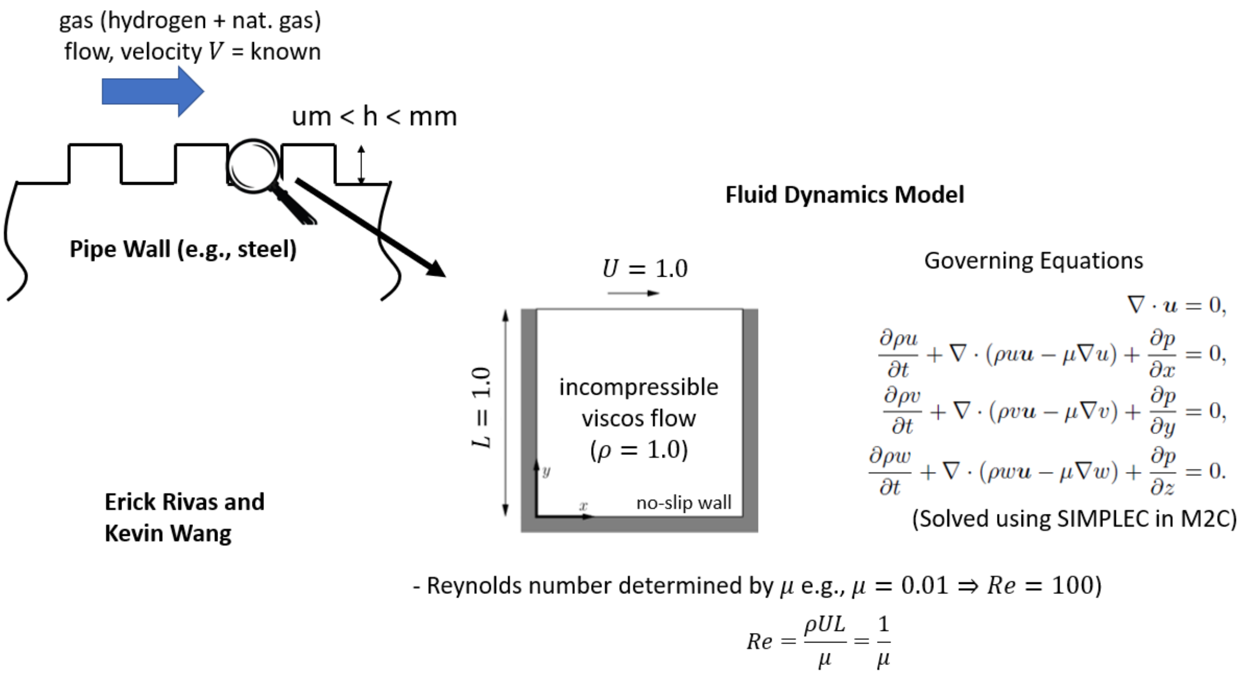
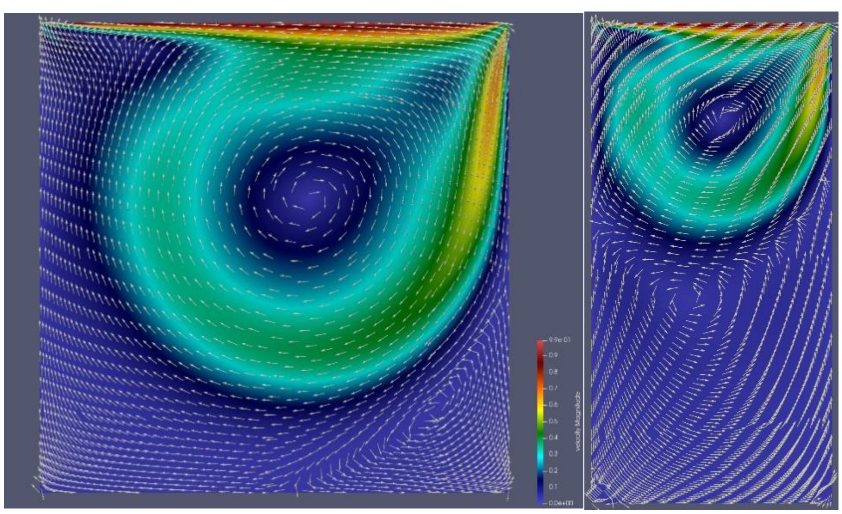


Figure 1: Development of the model problem and a benchmark test case

Figure 2 shows some example results. In these figures, the Reynolds number of the flow is fixed to 1000. The aspect ratio of the defect (assumed to be a rectangular cavity) varies between 0.5, 1, and 2. In all three cases, the vortex-dominated microflow within the cavity is captured clearly. The M2C code, developed by our team, can be adapted to any scenario we require. All results have been validated according to previous reports.



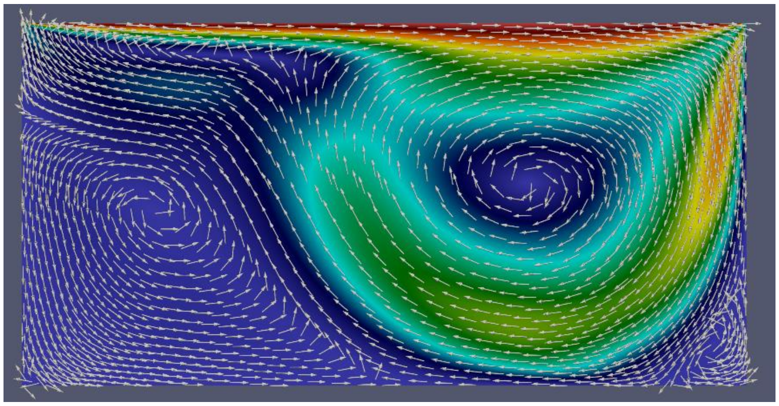


Figure 2: Simulation results of flow within a cavity, obtained using research code M2C with cavity aspect ratio 0.5, 1, and 2. (See Figure 1 for the model setup)

2) 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 track the transport of different species (hydrogen, air, and impurities) separately.
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 To determine component and system level factors that affect the hydrogen in the existing pipeline. In this quarter, the research team (Dr. Zhibin Lin, Dr. Hong Pan, Mohsin Ali Khan, and Xuanyu Zhou from NDSU) has explored stress corrosion cracking (SCC) effects as summarized below:

1) According to (PHMSA) reported (2008 to 2017), corrosion was the most significant incident causing pipeline failure (63%) followed by failure that occurred due to material/weld/equipment (17%) as shown in Figure 3. As corrosion is a broad term, it is essential to identify the types of corrosion causing pipeline failures.
Stress corrosion cracking (SSC) and Hydrogen Embrittlement (HE) are the main factors causing corrosion-based failures. Meanwhile, SSC can also trigger HE due to the production of hydrogen via corrosion processes. The broader prospect of SSC and HE is presented in Figure 3.

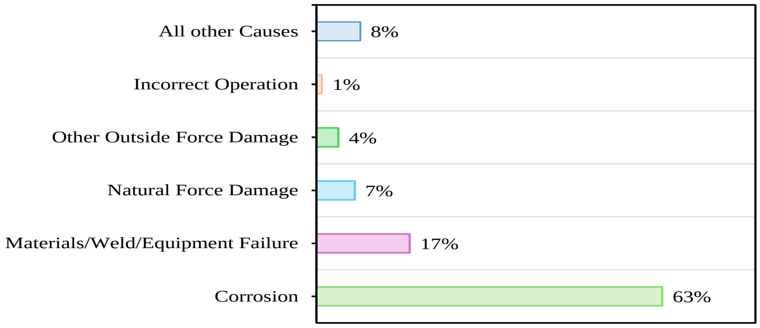


Figure 3: Incidents leading to pipeline failure

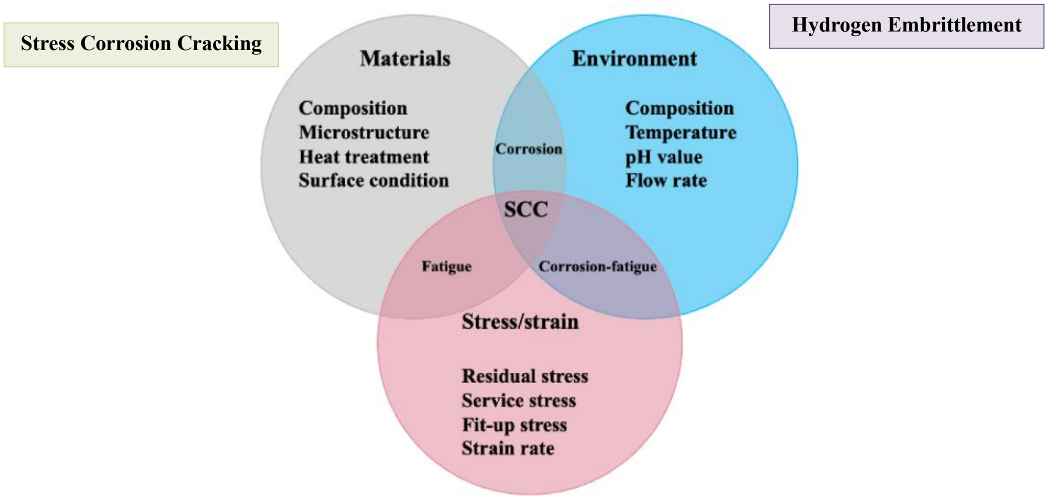


Figure 4: Factors affecting SCC and HE

2) The SSC crack growth rate can be well explained by the Bathtub model (proposed by Parkins. Crack growth depends on five sequential stages, all are presented in Figure 5, with a detailed explanation provided in Table 1. The crack initiation takes much longer times and depends on the quality of the surface of the material. As presented in Figure 6, the SSC initiation sites might be due to coarse machining/grinding marks (induced residual stress), Intergranular corrosion (sensitized locations), porosity in welds, and pitting, etc.

Table 1. Five sequential stages of SSC crack growth

Stage	**Crack growth mechanism**
Preparation stage	Conditions development (like the establishment of crack potential)
Stage 1a	Randomized formation of initial microcracks that merge and form shallow cracks, which eventually stop growing
Stage 1b	Expansion of early-stage cracks as nucleated microcracks link with the main crack tip, the nucleation of these microcracks is affected by the presence of prevailing main cracks
Stage 2	Beyond the threshold, the mechanical driving force influences the crack growth. **Constant loading:** Stage 2 growth starts when K >= KISCC **Cyclic loading:** Stage 2 growth starts when $\Delta K >= \Delta K_{th}$
Stage 3	Fast rupture

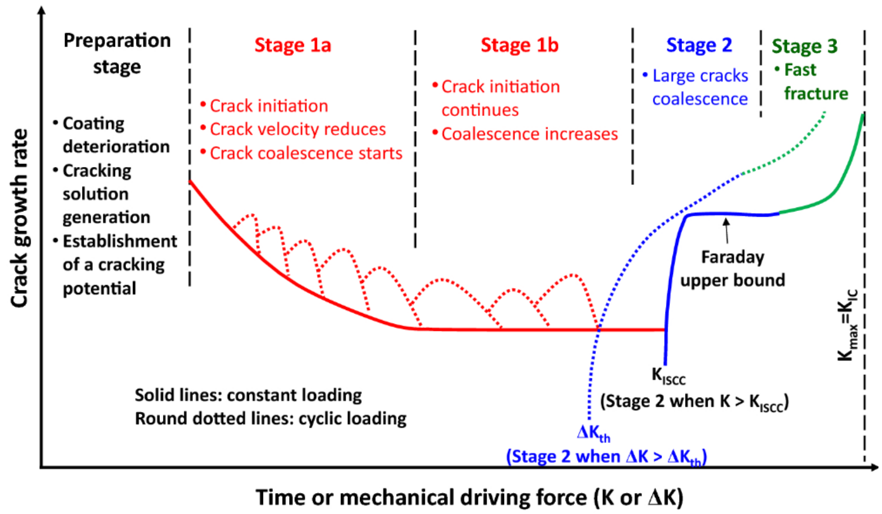


Figure 5: Relationship between the crack growth rate and the time or mechanical driving force for pipeline steel in SSC conditions.

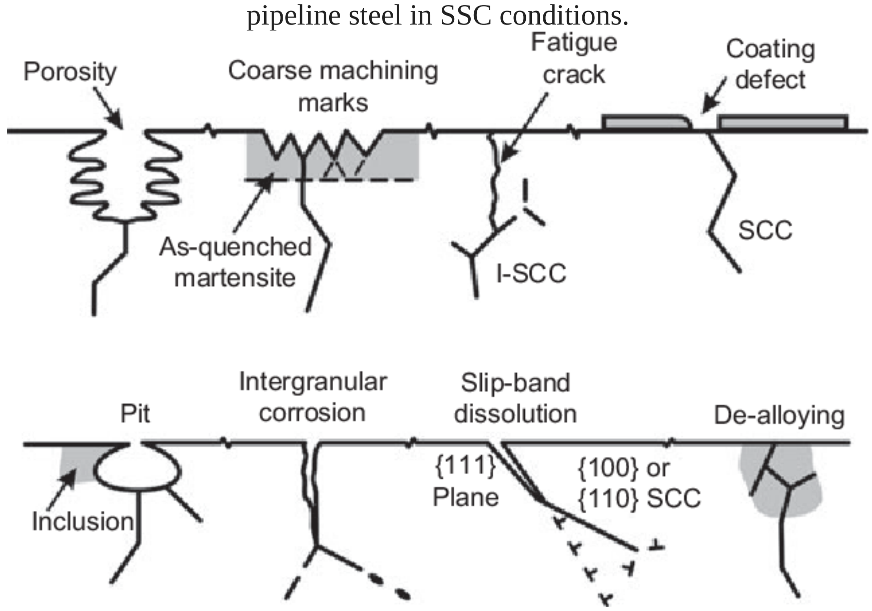


Figure 6: Frequently encountered sites of crack initiation in SCC conditions.

Task 6.1 Duo to the potential coupling effects of SCC and HE, the mitigation measurement is critical. Thus, during this quarter, the research team, comprised of Dr. Zhibin Lin, Dr. Hong Pan, Mohsin Ali Khan, and Xuanyu Zhou from NDSU, summarized the control measures for SCC, as outlined below:

1) To avoid the catastrophic failure of materials caused by stress corrosion cracking (SCC), regular inspection is the most immediate controlling measure. It is necessary to reduce the tensile stress on the material (by reducing the pressure in the pipeline) and control the environment. A detailed description is provided in Figure 7.

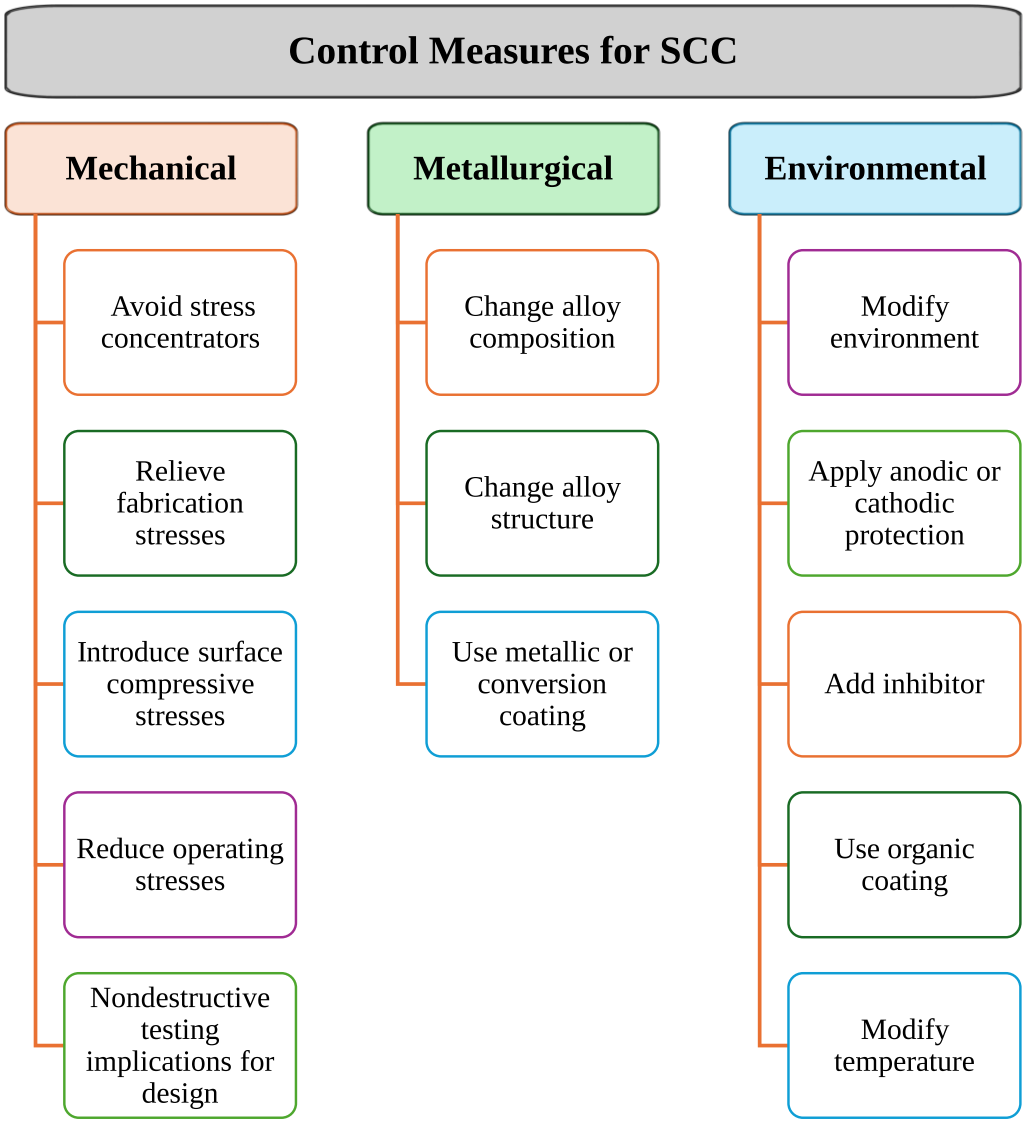


Figure 7. Main control measures for SCC.

Project Financial Activities Incurred during the Reporting Period:

The cost breakdown during the reporting period in each category according to the budget proposal is shown in Table 3. Note that the cost, particularly from subcontracts of the Co-PIs could be delayed from the process between organizations.

Table 3 Cost breakdown during the reporting period (Q7)

Category	Amount spent during Q7
Personnel	
Faculty	$10200
Postdoc	$9,000
Students (RA and UR)	$9,000
Benefits	$8,910
Operating Expenses	
Travel	$0
Materials and Supplies	$0
Recharge Center Fee	$0
Consultant Fee	$0
Subcontracts	Subawards issued
Indirect Costs	$16,700

Project Activities with Cost Share Partners:

The Match fund from NDSU for this project is coming from faculty academy hours of NDSU and Virginia Tech, and two Ph.D. students' RA tuition waivers. The matching fund from Dr. Lin (NDSU) and Dr. Wang (Virginia Tech) during Q5 is estimated to be $13,341, and the students' RA tuition waiver is about $16,560, so the total amount of match is estimated at $30,3901.

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 persist in their efforts on Tasks 3.1, 4.1,5.1, and 6.1, to depth the understanding of the hydrogen effects.

Potential Impacts on Pipeline Safety:

The summary of the SCC control measures provides reference and guidance to mitigate the SCC effect.