CAAP Quarterly Report

04/05/2024

Project Name: Development of Compatibility Assessment Model for Existing Pipelines for Handling Hydrogen-Containing Natural Gas

Contract Number: 693JK32250004CAAP

Prime University:

Prepared By: Ramadan Ahmed, r.ahmed@ou.edu, 405-473-7771

Reporting Period: 12/30/2023 – 03/29/2024

Project Activities for Reporting Period:

Members of the project team continued to maintain the master database to ensure that it contains the most recently measured hydrogen embrittlement data (HE) of carbon steel for pipeline applications (Task 1). As part of the database's ongoing maintenance, periodic data cleaning has been performed to detect and correct inaccuracies and inconsistencies. In addition, the team conducted laboratory experiments to determine how HE influences pipeline steel tensile behavior (Task 2.2). We have gathered more than 90 data sets showing the necking behavior of carbon steel, including reduction of area and maximum elongation before failure. We have examined the effects of material type, gas composition, pressure, temperature, and oxygen concentration on the tensile characteristics of the materials. Results are presented in the appendix (Fig. A-1). Regular experiments maintained a negligible amount of oxygen in the system (less than 2 ppm). Our next plan is to continue studying the fracture behavior of steel experimentally (Task 2.3), considering the various relevant factors.

We have developed a data integration strategy to address the data scarcity in machine learning for hydrogen embrittlement (HE) modeling in natural gas pipelines. This strategy merges data from various mechanical tests to enhance the prediction accuracy regarding HE's impact on metal strength. Our team developed Data Analytics-Based (DAB) models for primary and secondary outputs. Refining the secondary output models created in Task 3.1 can further refine the primary output models. These primary models, completed under Task 3.2, are focused on predicting carbon steels' fatigue strength and fracture characteristics. The findings in Appendix A reveal how hydrogen pressure and oxygen concentration affect pipeline steel's fracture toughness. Specifically, the fracture toughness below 1000 psi, a pressure range critical to most pipeline operations, shows heightened sensitivity to hydrogen partial pressure. Additionally, the models indicate that metal embrittlement is influenced by oxygen levels, particularly at concentrations under 20 ppm. However, due to a shortfall in database measurements, the model's predictions regarding oxygen's impact were less precise, leading to an underestimation. To enhance the accuracy of these predictions, further measurements at higher oxygen concentrations are essential.

Our team has prepared three scholarly articles for potential journal publication in the current reporting period. The first article has already been submitted to PHMSA for approval, while the other two are undergoing internal review and will be submitted very soon. These manuscripts focus on developing machine learning models to predict the fatigue strength and fracture toughness of pipeline materials.

Project Financial Activities Incurred during the Reporting Period:

Table 1 presents expenses during the reporting period in each budget category.

Table 1: Quarterly expense breakdown

Budget Category	DOT-PHMSA	OU Cost Share	Total
Salaries and Wages	$27,009	$7,913	$34,923
Fringe Benefits	$3,958	$2,722	$6,681
Equipment	$5,887	$0	$5,887
Travel	$590	$0	$590
Materials and Supplies	$8,220	$0	$8,220
Tuition	$22,045	$0	$22,045
Indirect Costs	$20,087	$5,850	$25,937
Total	**$87,797**	**$16,485**	**$104,282**

Note: Actual expenses may differ slightly from those presented in this table.

Project Activities with Cost Share Partners:

The Principal Investigator and co-PI participated in various research and development activities, such as supervising research assistants and technical staff, conducting hydrogen embrittlement research, and operating experimental setups.

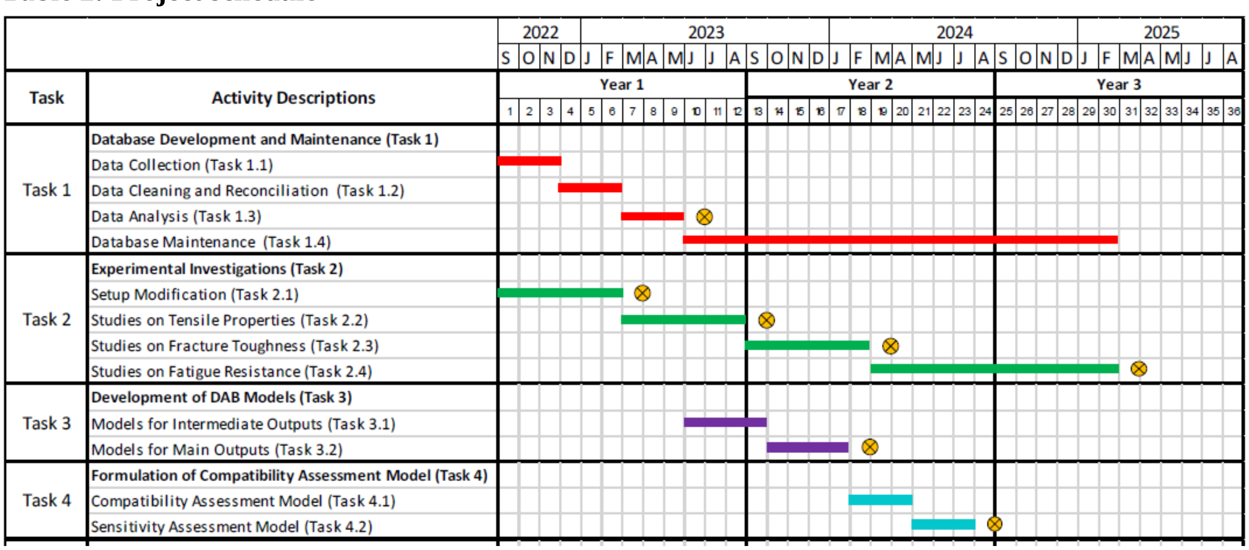
Project Activities with External Partners:

Not applicable.

Potential Project Risks:

By conducting parallel experimental studies (Tasks 2.3 and 2.4), we are compensating for the autoclave manufacturing delay. The delay is not expected to affect the project schedule (**Table 2**).

Table 2: Project schedule



Future Project Work:

In the scope of Task 2.3, our research group is dedicated to advancing our understanding of how pipeline steels behave in terms of fracture when exposed to environments rich in hydrogen. This phase of the research is set to cover material types. It will vary the concentrations of hydrogen and oxygen present, the rate at which the material is strained, the time the materials are aged, and the overall pressure within the system. The intent is to encompass a comprehensive range of conditions that mimic real-world scenarios.

In addition, our experimental research will examine and evaluate the fatigue resistance of pipeline steels when exposed to environments with high hydrogen concentrations. This segment of our study will thoroughly assess how varying levels of hydrogen and oxygen influence hydrogen embrittlement in these materials. We will also examine the impact of different load ratios, frequency of load fluctuations, and prevailing system pressures. Our goal with this investigation is to unearth the underlying mechanisms that affect the endurance and dependability of pipeline steels under such embrittlement conditions. By adopting a comprehensive research methodology, we are committed to enhancing the understanding of how pipeline steels withstand fatigue in hydrogen-rich atmospheres. We aim to provide critical insights that could guide the modification of existing pipelines for the safe transport of hydrogen and hydrogen-containing gases, thereby contributing valuable knowledge for the utilization of pipeline infrastructure as we transition to renewable energy resources.

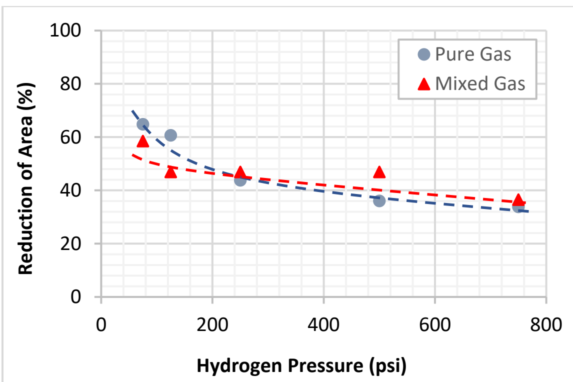
In the coming months, we will develop a model for compatibility for fitness-for-service (FFS) assessments, incorporating key outcomes from Task 3.2 alongside established guidelines (API 579-1/ASME FFS-1). The model addresses various pipeline failure scenarios, such as tensile, fracture, and fatigue damages. It conducts FFS evaluations and adjusts ratings for pipelines carrying pure or mixed hydrogen by employing conventional methods and utilizing the deteriorated material characteristics forecasted by the primary output models. Initially, we devised a powerful and dependable algorithm for the model, ensuring it delivers accurate forecasts. Utilizing this algorithm, we created software that aggregates data (such as pipeline material traits, gas mix, and operational parameters), executes both intermediate and primary models in a sequence to estimate the decline in material properties, and applies these estimates in the compatibility.

Potential Impacts to Pipeline Safety:

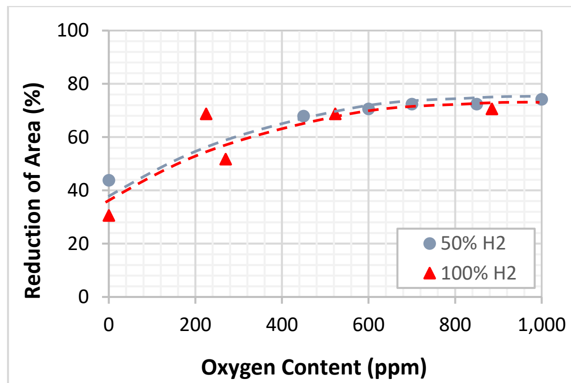
At this stage in our project, our machine-learning algorithms can predict the extent of hydrogen embrittlement (HE) that could happen when hydrogen is transported through existing gas pipelines. Thus, the predictions from our models can help define a safe operating range for transporting hydrogen in natural gas pipelines. To enhance the precision of these models, we'll include new experimental data from our current study and other significant research related to HE.

Appendix A: Results of experimental results from tensile testing (Task 2.1)

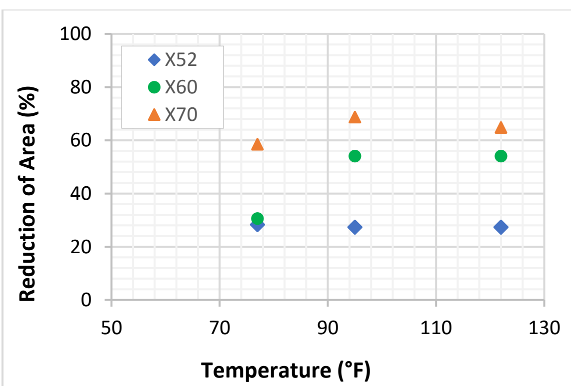
Figure A-1 displays the outcomes of tensile tests performed on various materials, highlighting the effect of key factors like hydrogen partial pressure, oxygen concentration, temperature, and material type on the reduction of area (RA), which indicates a material's ductility. A decrease in this parameter upon exposure is indicative of hydrogen embrittlement. The results align with prior research, confirming that RA diminishes with hydrogen pressure. Higher partial pressures lead to greater hydrogen dissolution in the material, thus exacerbating embrittlement and reducing RA. Studies using pure hydrogen and gas mixtures containing natural gas yielded similar findings, emphasizing that within mixed gases, the partial pressure of hydrogen singularly represents the hydrogen's effect, independent of natural gas presence.



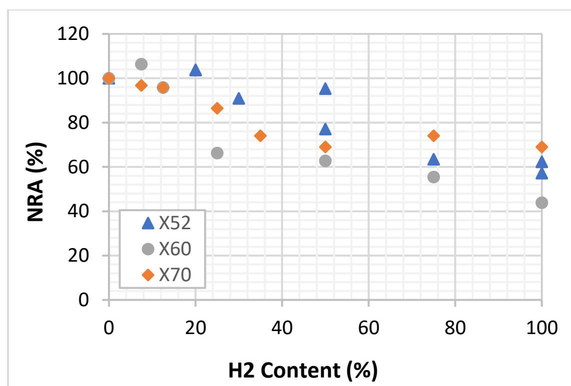
a) **Effect of hydrogen pressure – X52**



b) **Effects of oxygen content – X60**



c) **Effect of temperature – X60**



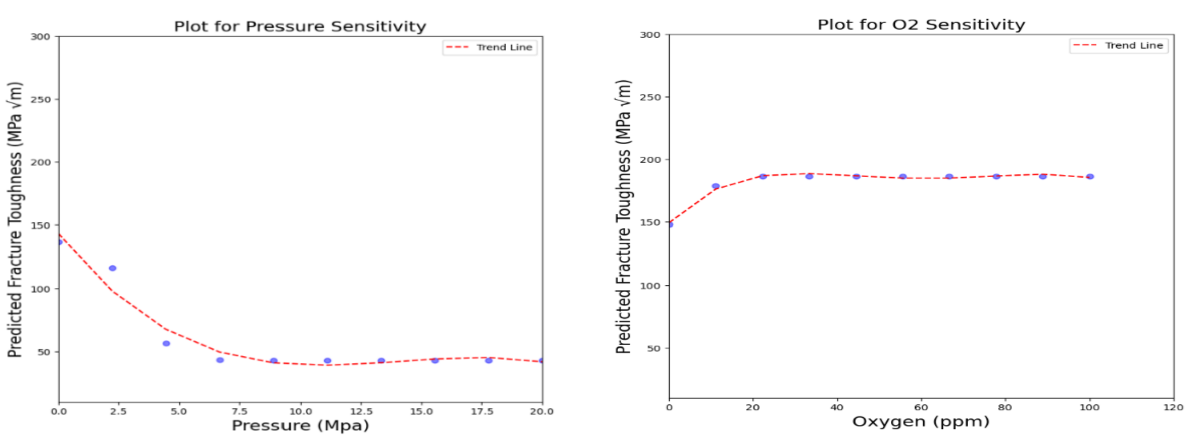
d) **Effect of material type**

Fig. A-1: Effects of H2 on reduction of area and elongation of pipeline carbon steel X52

The experiment adjusted the oxygen concentration between 1 and 1000 parts per million (ppm) to explore its influence on hydrogen embrittlement. Tests were conducted using both pure hydrogen and a mixture of gases. The findings indicated that the reduction in area (RA) trend was similar for pure hydrogen and a gas mixture with 50% natural gas. It was observed that introducing a minor amount of oxygen (1 – 1000 ppm) helped to maintain the material's ductility. The capability of oxygen to mitigate the effects of hydrogen embrittlement became more evident at lower concentrations. Despite the known issues of oxygen-inducing corrosion in pipelines, these results highlight its significant potential in managing hydrogen embrittlement effectively.

The impact of temperature on hydrogen embrittlement was also studied, revealing that its effect varies across different materials, as demonstrated by the patterns of reduction in area (RA) in relation to temperature. For the X52 material, a minor decrease in RA was noted as temperature rose, suggesting a slight increase in embrittlement with higher temperatures. This dual nature of temperature's influence on material ductility is noteworthy. On one hand, higher temperatures boost hydrogen's solubility and its diffusion into the material, leading to a loss of ductility. On the other hand, increased temperatures cause metals to become softer (thermal softening), enhancing ductility. The observed trends in RA reflect the combined consequences of these opposing effects. Consequently, the prevailing effect dictates the RA trend, with a minor reduction in the X52 material indicating a subtle predominance of the solubility effect. A different pattern was observed in other materials, such as X60 and X70. Between 77 and 92°F, RA values rose with temperature, but at higher temperatures (between 90 and 122°F), RA either slightly decreased or remained constant, signifying a shift in dominance away from the thermal softening regime.

The behavior of hydrogen embrittlement in different steel grades was studied by conducting experiments with mixed gas containing natural gas and hydrogen. Results revealed significant variations in ductility among the materials tested under normal conditions (i.e., without introducing hydrogen). The X70 grade displayed superior ductility compared to the others. Reduction Area (RA) values were normalized across all materials to equalize their baseline values without hydrogen for a fair comparison of embrittlement susceptibility to hydrogen. This normalization allowed for directly comparing their response to embrittlement facilitating environments. Results from the normalized RA (NRA) measurements indicated slight differences among the pipeline materials as the hydrogen content in the gas increased. All materials experienced a decline in NRA with an increase in hydrogen concentration. Notably, NRA values differed significantly as the hydrogen concentration neared 100%. The X60 grade showed the greatest embrittlement, with a 56% reduction in NRA, indicating it was most adversely affected by hydrogen. Conversely, X70 was the least affected, with a 31% decrease in NRA, highlighting its relative resistance to hydrogen embrittlement. The X52 grade's ductility was affected to an intermediate extent, with a maximum NRA reduction of about 40%, suggesting a moderate susceptibility to hydrogen content.



(a) (b)

Fig. A-2: The effects of hydrogen pressure (a) and oxygen content (b) on fracture toughness