CAAP Quarterly Report

December 30, 2024

Project Name: Enhancing Knowledge and Technology to Prevent and Mitigate Risks of Stress Corrosion Cracking (SCC) for Pipeline Integrity Management

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Prime University: Stevens Institute of Technology

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Reporting Period: [09/30/2024-12/30/2024]

Project Activities for Reporting Period:

In this quarter, three primary activities were performed successfully, which are (1) a kick-off meeting on November 4th, 2024, and meetings within this multi-institute collaborative research team; (2) recruitment of three graduate students (Ms. Shengju Xie and Mr. Yao Wang at Stevens Institute of Technology and Mr. Samuel Ajayi at North Dakota State University); and (3) partial completion of the literature review task (Task I), covering basic knowledge about pipeline SCC, monitoring techniques for pipeline SCC, and risk mitigation solutions.

The participants of the kick-off meeting include the PHMSA program manager team, four PI/co-PIs, two graduate students, and one consultant. In the kick-off meeting, the PI presented the research proposal, followed by discussion on the tasks and potential risks. In particular, two primary risks were deeply discussed, which are the project timeline and testbed preparation. The mitigation strategies are closely monitoring project progress and communicating with the project manager team. The team plans to have biweekly meetings to discuss progress and plan for the next step, ensuring that risks are identified and addressed on a timely basis.

Three graduate students have been recruited. Shengju Xie and Yao Wang were recruited via the Provost's Doctoral Fellowship Program at Stevens Institute of Technology. The Fellowship provides financial support for one year, benefiting the team via filling the gap for recruiting new students and minimizing delays of research progress. Shengju Xie and Yao Wang have started the literature review tasks and partially completed Task 1. Samuel Ajayi, a Ph.D. student, has been recruited and will work on this project at North Dakota State University and contributed to the literature review.

Task I focuses on a comprehensive review of prior research, current industry standards, and best practices related to pipeline SCC. There are two subtasks. The first subtask focuses on prior research developed by stakeholders regarding SCC. The review has been conducted proactively by defining keywords, identifying databases for collecting relevant references, and selecting appropriate publications. The second subtask focuses on examining the applicability of industry standards related to pipeline SCC and surveying the best practices for preventing and mitigating risks associated with pipeline SCC.

Research on basic knowledge about pipeline SCC and monitoring methods were reviewed in this quarter. The main reviewed contents on these two aspects are summarized as follows:

1. Basic knowledge

1.1 What is pipeline SCC?

Pipeline SCC is a degradation caused by the interaction between corrosion and mechanical stress, typically occurring at locations with metallurgical defects. SCC propagates slowly in its early stages; however, once the crack reaches a critical length, its growth rate accelerates, leading to pipeline failure within a short period.

Understanding the mechanisms of SCC, monitoring SCC severity, and assessing pipeline health conditions play crucial roles in pipeline integrity management. The occurrence of SCC requires three conditions, which are (1) susceptible metallurgy, (2) a corrosive environment, and (3) pipe wall stress. Controlling these conditions can help mitigate the occurrence of pipeline SCC. Metallurgical factors, such as steel grade, alloy composition, microstructure (grain size, grain boundary distribution, and texture), and metallurgical defects (inclusions, surface irregularities, and residual stresses) influence the initiation and propagation of SCC. However, for vintage pipeline steel that has already undergone SCC, metallurgical factors are inherent and unavoidable. Therefore, the effects of metallurgical factors and defects on SCC are not covered in the main body of the report, relevant details are provided in the appendix. Moreover, cathodic protection and recoating are effective strategies for mitigating SCC progression in existing pipelines [1].

1.2. What are the effects of environmental variables on SCC?

Given the diverse environmental conditions for pipelines, it is crucial to understand the mechanisms and characteristics of SCC in various environments for pipeline management, risk evaluation, and integrity maintenance [2]. Existing studies have shown that both individual and combined factors (e.g., temperature, humidity, pH, corrosive deposits, microorganisms, oxygen and carbon dioxide concentrations) influence the electrochemical reactions involved in the steel corrosion process [3-8].

Pipeline SCC typically occurs at locations where coating debonding has occurred, allowing an electrolyte to form between the damaged coating and the line pipe steel substrate. Depending on the pH of the electrolyte, SCC is generally classified into high-pH SCC or near-neutral pH SCC. The formation of high-pH electrolytes is caused by concentrated carbonate-bicarbonate solutions, with a pH value over 9.3, while near-neutral pH electrolytes are associated with diluted bicarbonate solutions, with a pH range of 5.5 to 7.5 [9]. The corrosion mechanisms and crack features of high-pH and near-neutral pH SCC are distinct. High-pH SCC is primarily driven by anodic dissolution, leading to intergranular cracking with small branching. However, near-neutral pH SCC is associated with dissolution at the crack tip and sides, often accompanied by HIC. This type of SCC typically exhibits transgranular cracking, with corrosion observed along the crack sidewalls, and the crack width tends to be wider compared to high-pH SCC [10]. The application of pipelines is not confined to near-neutral and high-pH environments but also extends to acidic environments.

Liu et al. [11] studied the SCC of X70 pipe steel in the acidic soil solution. Experimental results show that the dominant mechanisms of SCC development vary with applied potentials. In general, elevated temperatures accelerate most electrochemical processes [3,12]. SCC is more likely to occur in high-temperature regions like pipelines downstream of compressor stations. Contreras et al. [13] investigated the influence of pH and temperature on the SCC behavior of API X60 pipeline steel. The results reveal that API X60 pipeline steel exhibits susceptibility to SCC in low-pH (pH = 3) environments. Additionally, the impact of temperature on steel's SCC susceptibility is more significant in high-pH environments than in low-pH and near-neutral pH environments [9,13]. Moreover, improper application of external cathodic protection accelerated the initiation and propagation of SCC in steel [14].

The initiation and propagation of SCC are divided into four stages, including (1) Incubation stage: This stage involves the formation of corrosion environments, such as coating debonding, electrolyte accumulation, and improper cathodic protection; (2) Crack initiation and coalescence stage: In this stage, crack density increased, and coalescence between cracks occurs; (3) Crack growth stage; and (4) Rapid growth to rupture stage [15-17]. Tensile stress in the pipe wall plays a crucial role in the crack growth stage of SCC [18].

1.3. What are the effects of pipeline stresses on SCC?

Stress in pipelines is primarily induced by internal pressure from transported gases or liquids, along with the weight of overlying soil and uneven settlement. Based on the direction of the stress, it can be categorized as circumferential stress (hoop stress) along the pipe’s circumference and longitudinal stress along the pipe’s axis. Crack propagation typically occurs perpendicular to the direction of the pipeline wall stress [9]. The stress intensity factor (SIF), which is related to the stress state at the crack tip, is introduced as a parameter for analyzing the crack propagation rate. Crack geometry, location, and applied load all influence the SIF [18]. Song et al. [19,20] conducted a study on predicting the crack growth rate of buried steel pipes under high-pH stress corrosion conditions.

Another type of tensile stress that contributes to the development of pipeline SCC is residual stress. Residual stress can arise from factors such as steel metallurgy, welding, bending, and heat treatment processes [21]. Based on length scale, residual stresses can be classified into three types, including (i) macro-scale residual stresses, (ii) micro-scale residual stresses, and (iii) atomic-scale residual stresses [22]. Chen et al. [23] investigated the influence of type I residual stresses on the initiation of pitting corrosion and SCC. The results indicate that stress cycling during the operational process alters the distribution of residual stress. As the residual stress gradient near the surface shifts — from a high tensile state to a lower tensile or compressive state — due to self-equilibration, active cracks may become dormant. This alteration in residual stress, which occurs within 1 mm of the surface, results in a significant proportion of dormant SCC. More effort needs to be made to understand the pipeline SCC mechanism under various environments.

1.4. What are existing knowledge gaps about pipeline SCC?

Accordingly, the main gaps are summarized as below:

(1) Some important factors, such as pressure cycling, temperature cycling, and metallurgy, have not been fully studied. The insufficient study of these factors creates gaps in the current understanding of pipeline SCC, which in turn hinders the development of effective strategies for pipeline operation and management, ultimately affecting the pipeline's service life; and

(2) The coupling effect of different factors has not been fully investigated. In natural environments, the numerous and complex factors influencing pipeline SCC make it challenging to accurately assess the impact of coupled factors. In experimental settings, research is constrained by limitations in experimental equipment and the long-term nature of SCC development, which requires extended observation periods. Additionally, integrating theoretical mechanisms of SCC with experimental data to gain deeper insight into the effects of coupled factors remains a significant challenge.

Further research is needed to better understand the mechanisms and mitigation strategies for pipeline SCC under different environmental and operational conditions.

2. Monitoring techniques

Effective pipeline monitoring and assessment are crucial for preventing pipeline accidents. Various techniques, including destructive and nondestructive evaluation methods, have been developed for detecting and characterizing SCC. In the first quarter, we reviewed promising inspection and monitoring technologies of real-time monitoring for pipeline SCC, such as acoustic emission [24,25], ultrasonic testing [26,27], eddy current testing [28,29], and direct current potential drop [30,31]. Research gaps and future research issues that require attention in the field of real-time monitoring for pipeline SCC are discussed.

2.1. What are recommendations by relevant standards?

The National Association of Corrosion Engineers (NACE) SP0204 outlines a comprehensive procedure guiding the direct assessment of buried pipelines, applicable to both near-neutral-pH SCC and high-pH SCC [32]. The procedure involves four main steps for direct assessment of buried pipelines, including a pre-assessment (in which the operator determines the feasibility of external corrosion direct assessment, determines external corrosion direct assessment regions, and selects tools for indirect inspection), an indirect inspection (in which the operator conducts above-ground inspections, such as a close interval survey, to identify and classify indicators of corrosion and pipe coating defects), a direct examination (in which the operator excavates the pipe at selected locations to measure actual corrosion damage), and a post-assessment (when the operator determines reassessment intervals and evaluates the effectiveness of the external corrosion direct assessment process).

2.2. What are existing methods for monitoring pipeline SCC?

Researchers have developed various methods to monitor pipeline SCC, such as acoustic emission, ultrasonic testing, and eddy current testing. These methods utilize sound or electromagnetic waves to inspect or monitor materials. When SCC occurs within the material, it generates sound waves and alters properties of material [24,26,33]. Additionally, it can cause phenomena like reflection and refraction of ultrasonic waves. These ultimately enable the monitoring of SCC. Specifically, these methods can be summarized into three categories as below:

a. Electrochemical methods
b. Acoustic methods, such as acoustic emission and ultrasonic testing
c. Electromagnetism methods, such as eddy current testing, direct current potential drop, and other electromagnetism methods

2.3. What are the limitations of existing methods for monitoring pipeline SCC?

Each method has its own limitations. For example, acoustic monitoring and electromagnetic methods generate large volumes of data, making analysis difficult. Acoustic monitoring results are influenced by uneven properties within the material, while electromagnetic methods are often ineffective in monitoring SCC in thick materials. The most commonly used methods include acoustic methods (e.g., acoustic emission and ultrasonic testing), and electromagnetic wave methods (e.g., eddy current testing and direct current potential drop). The principles, strengths, and weaknesses of these methods have been reviewed. Due to page limitations, they are not detailed.

3. Machine learning aided SCC monitoring

Machine learning has become a powerful tool in addressing challenges in monitoring SCC, especially in signal processing. It can accomplish complex tasks that would otherwise require human effort. Additionally, it can assist in on-site monitoring, enabling real-time monitoring. This is primarily reflected in the real-time acquisition and processing of monitoring signals, as well as crack image recognition. Currently, machine learning-assisted SCC monitoring is applied in very limited situations, such as using machine learning regression models to predict the length and depth of SCC [29], SCC growth rate [34,35], and so on. Using a machine learning classification model to classify the severity levels of SCC [36], distinguish the crack type [37]. The application of machine learning methods in SCC monitoring has been limited to date. Integrating machine learning into monitoring processes, such as acoustic signal processing and crack image recognition, holds significant potential to improve both efficiency and accuracy, making it a crucial focus for future research.

Project Financial Activities Incurred during the Reporting Period:

The Prime university (Stevens Institute of Technology) fully executed the agreement with the PHMSA and sub-universities (North Dakota State University and Rutgers University).

Project Activities with Cost Share Partners:

There were no major activities that were conducted during this reporting period with cost share partners.

Project Activities with External Partners:

The primary activities that were conducted during this reporting period with external partners or sub-universities include: (1) the kick-off meeting on November 4th, 2024; (2) recruitment of graduate student (Mr. Samuel Ajayi at North Dakota State University); and (3) collaborative effort for the literature review task (Task I).

Potential Project Risks:

We have not identified major projects risks. The project is progressing as planned.

Future Project Work:

In the next 30 days, we aim to complete the literature review tasks for Task I. Based on the review, we will draft a technical paper and circulate the draft paper among the project team for refinement. In the next 60 days, we aim to submit the paper to a journal for peer review and improvement of the quality. We will also start to prepare for the activities in Task II. In the next 90 days, we aim to complete the preparation activities and be ready to start activities in Task II.

Potential Impacts to Pipeline Safety:

There are four main impacts: (1) *Improved Understanding of SCC Mechanisms*: The literature review enhances the understanding of SCC mechanisms, including the roles of metallurgical defects, environmental variables, and pipeline stresses. This knowledge contributes to better design experiments for investigating the effects of casual factors of pipeline SCC under various operational and environmental conditions. Insights from reviewed studies on SCC in high-pH, near-neutral pH, and acidic environments directly support the development of effective risk mitigation measures. (2) *Identification of Knowledge Gaps*: By summarizing existing gaps, such as limited understanding of coupled factors (e.g., temperature and pressure cycling) and long-term SCC behavior, the project provides a roadmap for targeted research. (3) *Enhancement of Monitoring Techniques*: The review of real-time SCC monitoring methods facilitates improved accuracy and efficiency in monitoring, reducing the likelihood of failures. By highlighting the weaknesses of existing methods (e.g., large data volumes, ineffectiveness in thick materials), the project identifies opportunities for innovative approaches, such as machine learning-assisted signal processing. (4) *Collaborative Efforts for Timely Risk Mitigation*. The kick-off meeting and biweekly discussions ensure that potential risks, such as delays in the project timeline or testbed preparation, are monitored and mitigated proactively. This collaborative approach strengthens the project's capacity to maintain alignment with safety-critical milestones and deliver timely recommendations for industry adoption. (5) *Foundation for Advanced Research and Application*: The recruitment of graduate students and initial research efforts provide the human capital and knowledge base needed for subsequent project phases, including experimental studies and advanced risk models. This supports the development of unified safety models for pipelines and long-term improvement in pipeline integrity management practices.

Appendix

This appendix provides a brief review of the effects of metallurgical factors and defects on SCC. The metallurgical factors are not the focus of this project. Considering they are important for a holistic understanding of SCC, the brief review is presented below.

1. What are the effects of metallurgical factors on SCC?

Lu et al. [38-40] investigated the correlation between yield strength and SCC resistance in near-neutral pH environments by conducting Slow Strain Rate Tensile (SSRT) tests on API 5L X52, X60, X65, X70, X80, and X100 grade steels, considering different heat treatment methods. The results indicate that SCC resistance generally decreases with increasing steel yield strength, but this relationship is significantly influenced by microstructure. Therefore, assessing SCC resistance requires consideration of both yield strength and microstructural characteristics.

In addition, Zhu et al. [41] conducted SSRT tests to study the SCC behavior of Chinese X80 pipeline steel with varying strengths and microstructures in high-pH environments. The results revealed that both strength and microstructure significantly affect the SCC cracking mode. The yield strength and microstructure of steel are influenced by its composition and manufacturing processes. Therefore, optimizing the elemental composition and refining the microstructure are effective strategies for mitigating pipeline SCC [18,42].

2. What are the effects of metallurgical defects on SCC?

The presence of inclusions promotes the initiation of the pipeline SCC. First, the disparity in thermal expansion coefficients between inclusions and the steel matrix induces internal stresses and potential crack initiation due to the inconsistent volume changes under temperature fluctuations [43]. Second, the different Young's moduli and irregular contact surfaces between the inclusion and steel matrix led to high stress concentration, which could result in the initiation of SCC cracks [43]. Additionally, the micro-crevices between inclusion and matrix serve as sites for hydrogen penetration. When hydrogen molecules accumulate and reach a certain concentration, the resulting gas pressure generates high local stresses, which can lead to crack initiation at the weak interfaces within steel [44]. The formation of cracks due to excessive localized stress from hydrogen accumulation is known as hydrogen-induced cracking (HIC).

The susceptibility of steel to SCC is significantly influenced by surface irregularities. A rough surface can (i) create stress concentrations, (ii) trap corrosive media, and (iii) increase the likelihood of surface defects, thereby increasing the risk of hydrogen ingress. Furthermore, concentration gradients of corrosive media between microscopic pits and protrusions accelerates localized corrosion, further compromising the steel's resistance to SCC. To address this issue, appropriate surface treatments and protective coatings can enhance the integrity of the machined surface and isolate corrosive media from steel matrix, thereby effectively improving resistance to SCC [45,46]. Surface treatment methods, such as sand blasting, wire brushing, grit blasting, grinding, milling, and turning, can enhance surface smoothness and improve the adhesion between steel and coatings. However, localized plastic deformation and thermal effects induced by surface treatments cause residual stress and phase transformation [47,48]. Extensive research has been conducted on the influence of surface treatment methods on SCC in steel [49-51].

References

We have reviewed over 100 references. Due to page limitations, only some of the references are listed as follows. More references will be provided in the next report (2nd quarterly report), and a complete list of references will be provided in a review paper.

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