CAAP Annual Report

Date of Report: *10/30/2025*

Prepared for: *U.S. DOT Pipeline and Hazardous Materials Safety Administration*

Annual Period: From *(September 01, 2024)* **to** *(September 30, 2025)*

Contract Number: *693JK32450002CAAP*

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

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Section A: Business and Activities

(a) Contract Activities

- Contract Modifications:

  No modifications.

- Educational Activities:
  - Student mentoring:

The students participating in this project include two Ph.D. students from Stevens Institute of Technology, Ms. Shengju Xie and Mr. Yao Wang, and one Ph.D. student from North Dakota State University, Mr. Samuel Ajayi. These students have been supervised by the PIs/co-PIs and one consultant. Shengju Xie has focused on studying SCC mechanisms, influencing factors, and mitigation measures. Yao Wang has focused on developing SCC monitoring methods. Samuel Ajayi has contributed to both mitigation measures and monitoring technologies.

  - Student internship:

No internship yet.

  - Educational activities:

(1) Pipeline operating conditions consultation

The industry consultant provided practical insights based on field experience regarding commonly used pipeline steels for oil and gas transportation, their typical dimensions, operating temperature ranges, and pressure fluctuation cycles. These inputs were incorporated to determine the final experimental parameters.

(2) MTS 810 material testing system training

The students received systematic training on the MTS 810 material test system. The training covered testing protocols, system components, operating procedures, and safety precautions.

(3) Laboratory safety and fume hood training

The training covered the identification of chemical hazard symbols, the safe handling and storage of laboratory reagents, and the preparation of corrosion solutions representative of near-neutral pH environments for pipeline steel testing, with proper use of the fume hood.

(4) Acoustic emission training

The training for acoustic emission (AE) includes sensor mounting, system configuration, signal denoising, and fracture-like signal analysis. During the training phase and preliminary experiments, the optimal acoustic couplant, sensor fixation method, and monitoring threshold were determined for the formal tests.

(5) Ultrasonic non-destructive testing training

During the ultrasonic non-destructive testing training, dispersion analysis and guided wave detection were trained. A preliminary analysis was performed based on steel pipes to determine the ultrasonic excitation frequency and select appropriate transducers. Training also involved conducting guided wave tests on both dog-bone and plate specimens by transmitting a 5-cycle tone burst wave.

  - Career employed: None
  - Others: None

- Dissemination of Project Outcomes:

Two review papers titled “Review of Nondestructive Evaluation Techniques for Pipeline Stress Corrosion Cracking” and “Review of Nondestructive Evaluation Techniques for Pipeline Stress Corrosion Cracking” have been submitted to journals for peer-review.

- Citations of The Publications: None
- Others: None

(b) Financial Summary

- Federal Cost Activities:
  - PI/Co-PIs/students involvement:

    Yi Bao, Ying Huang, Shengju Xie, Yao Wang

  - Materials purchased/travel/contractual (consultants/subcontractors):

    Experimental testing materials

- Cost Share Activities:
  - Cost share contribution:

The tuition and stipend of graduate students (Shengju Xie, Yao Wang) were covered by the Provost’s Fellowship of Stevens Institute of Technology.

(c) Project Schedule Update

- Project Schedule:

The current project progress is slightly behind the schedule outlined in the proposal. According to the proposal, experimental studies on the effects of individual influencing factors on SCC were expected to begin in the third quarter. Due to delayed fabrication of specimens, the experiments were started from the fourth quarter. The delay resulted from the delayed delivery of pipeline steel and the delayed fabrication of specimens. The delayed fabrication was caused by the machine shop’s capacity. Unlike flat steel plates, pipelines present additional challenges in specimen preparation, requiring close discussion with the machine shop to develop appropriate fabrication procedures. These challenges have been solved, and we will accelerate progress and catch up in the fifth quarter.

- Corrective Actions:

In the next quarter, we will accelerate progress in experimental testing of specimens.

(d) Status Update of the 4th Quarter Technical Activities

- Task I: Literature review

This task was already completed. The literature review activities led to the production of two review papers besides the progress reports. The two papers were submitted to two journals for peer review, and they are currently pending for publication. Regarding the progress reports, we received comprehensive, constructive suggestions from the project manager and utilized the feedback to revise the report.

Paper 1's title: "Review of Nondestructive Evaluation Techniques for Pipeline Stress Corrosion Cracking", led by Mr. Yao Wang

Paper 2's title: "A Review on Pipeline Stress Corrosion Cracking (SCC): Mechanisms, Causal Factors, Predictive Models, and Mitigation Strategies", led by Ms. Shengju Xie

- Task II: Investigation of multiple causal factors of pipeline SCC and development of the innovative multi-scale monitoring technique

We have partially completed this task. Specifically, we have prepared the experimental test setup and completed the preliminary tests for verification of the test setup before formal testing. We have partially completed the fabrication of test specimens and have started the formal testing using specimens that were already fabricated. Currently, we are working with the machine shop at Stevens Institute of Technology to fabricate the remaining specimens. The progress of the third quarter was slightly delayed, as stated in section (c) Project Schedule Update. We have accelerated progress in the fifth quarter and are trying to catch up.

- Task III – Recommendations for preventive and repair criteria

We have not started this task yet. This is consistent with the timeline in the proposal.

- Task IV – Education, dissemination, and reporting

Three Ph.D. students were trained, as stated in "Educational Activities" of section (a) Contract Activities. Two full-length journal papers were produced and submitted for peer review. Mr. Yao Wang attended the annual conference of New Jersey's Department of Transportation and delivered an oral presentation on acoustic emission-based structural monitoring based on his research outcomes. Quarterly progress reports were submitted to and reviewed by the project manager. The reports were revised according to the project manager's feedback and approved.

Section B: Detailed Technical Results in the Report Period

1. Background and Objectives in the 1st Annual Report Period

1.1 Background

According to PHMSA, oil and natural gas together account for approximately 65% of the total energy supply in the United States, making them the dominant sources of national energy consumption [1]. Pipeline systems are widely used for oil and gas transportation owing to their high efficiency, reliability, and economic advantages. As reported by PHMSA, approximately 2.78 million miles of pipelines are currently in service for gas distribution, gathering, and transmission, while about 228,711 miles are utilized for the gathering and transmission of liquid commodities [2]. However, long-distance exposure to complex topography and diverse environmental conditions increases the risk of pipeline failures, which may lead to significant economic losses, energy supply disruptions, environmental pollution, and even casualties. Accordingly, significant efforts and investments in inspection and maintenance have been made to maintain pipeline integrity and ensure operational safety. For instance, PHMSA's Office of Pipeline Safety personnel devoted 64% of their time to safety-related activities, including inspections and failure investigations conducted in the field, laboratory, and office [3].

The primary causal factors of pipeline incidents include third-party damage, corrosion, natural hazards, incorrect operation, manufacturing defects, and SCC [4]. SCC is a widespread issue threatening pipeline safety [5], yet the industry's understanding of SCC is still to be advanced, and practical solutions for reducing SCC risks are not as mature as the methods for addressing other causal factors of pipeline incidents.

Since the mid-1960s, when high-pH SCC failures were first reported in high-pressure gas transmission pipelines, the issue of SCC has attracted widespread attention [6]. SCC occurs under synergistic interactions of metallurgical defects, environmental corrosion, and mechanical stress [7]. Its development mechanism involves the fields of electrochemistry, metallurgy, and mechanics. Additionally, the dominant factors in SCC development vary at different stages [8,9]. The complexity of SCC mechanisms and numerous influencing factors have constrained our understanding, impeding further progress in pipeline safety and management.

In addition, effective pipeline SCC monitoring techniques are crucial for assessing pipeline integrity, thereby reducing the risk of incidents such as leaks and ruptures. It also contributes to expanding the data repository for future safety assessment and repair decision-making under varying conditions. Early practices rely on visual inspection, which is inefficient in time and labor. Recently, various techniques have been developed to monitor SCC, such as techniques based on sound waves [10,11], electrical current [12,13], and chemical composition [14,15].

1.2 Objectives in the 1st Annual Report Period

The primary objectives of this period are (1) to conduct a comprehensive literature review of previous studies on SCC, including its underlying mechanisms, influencing factors, monitoring techniques, predictive models, and future challenges and opportunities; and (2) to conduct research activities on the effects of individual causal factors on pipeline SCC based on the literature review and discussions with the consultant.

To achieve these objectives, we have performed eight primary activities:

(1) A kick-off meeting on November 4^{th}, 2024, and meetings within this multi-institute collaborative research team. (1st quarter)

(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). (1st quarter)

(3) Two comprehensive reviews, integrating knowledge about SCC based on prior research and current industry standards and practices, were written and submitted to journal for peer-review. (2nd & 3rd quarter)

(4) Consultation with an industry expert was conducted to ensure the experimental design was both accurate and practical for on-site application. (2nd & 3rd quarter)

(5) The experimental plan for investigating the effects of individual factors on pipeline SCC was designed. (3rd & 4th quarter)

(6) Students are trained in the use of experimental systems, including MTS, AE, and Ultrasonic Testing (UT). (3rd & 4th quarter)

(7) Experimental testing was conducted to examine the experimental test setup and plans and to refine the experimental design. (4th quarter)

(8) Fabrication of test specimens was performed through the collaboration with the machine shop at Stevens Institute of Technology. (4th quarter)

2. Experimental Program in the 1st Annual Report Period

2.1 Experimental Design

2.1.1 Experimental parameters

The experimental design for investigating the effects of individual causal factors on SCC is shown in **Table 1**. The individual factors considered in this study include pressure cycling, temperature cycling, soil conditions, steel grade, heat treatment, and welding. Following an extensive review of relevant literature, we established a set of parameters for these causal factors based on existing studies. Several parameters related to pressure cycling have been refined based on communications with industry partners to ensure practical relevance and applicability.

Table 1. Design of experimental for individual causal factors

Causal factor	Pressure cycling		Temperature cycling		Soil condition		Metallurgy		Welding method
	Amp.	Freq.	Amp.	Freq.	Concen.	pH	Grade	Treatment	
Control	PCA1	NA	TCA1	NA	C1	pH2	G1	T1	W1
Pressure cycling	PCA1 to PCA3	PCF1	TCA1	NA	C1	pH2	G1	T1	W1
Temperature cycling	PCA1	NA	TCA1 to TCA3	TCF1 to TCF3	C1	pH2	G1	T1	W1
Soil condition	PCA1	NA	TCA1	NA	C1 to C3	pH1-pH3	G1	T1	W1
Pipe grade	PCA1	NA	TCA1	NA	C1	pH2	G1 to G3	T1	W1
Treatment	PCA1	NA	TCA1	NA	C1	pH2	G1	T1 to T3	W1
Welding	PCA1	NA	TCA1	NA	C1	pH2	G1	T1	W1, W2

Note: Amp. = Amplitude, Freq. = Frequency, and Concen. = Concentration.

Information about pipeline steels X42, X52, and X65 is summarized in **Table 2**.

Table 2. Steel pipe information

Steel grade	Welding methods	Heat treatment	PSL	OD (in)	Wall (in)	End finish
X42	Seamless	Normalized	PSL 2	4.5	0.237	Plain end beveled
X52M	High frequency welded	Weld seam annealing, Thermomechanical rolled or thermomechanical formed	PSL 2	4.5	0.237	---
X65Q	Seamless	Quench and tempered	PSL 2	4.5	0.237	Plain end beveled

Steel grade. API 5L X42 and X52 are typical steel grades employed in vintage pipelines, and X65 is one of the most widely used pipeline steels in both practical applications and academic research [16]. Accordingly, X42 (G1), X52 (G2), and X65 (G3) are selected to investigate the effect of steel grade on SCC.

Welding methods. Seamless (W1) and High-frequency electric resistance welding (W2) are selected for this project to investigate the effect of welding method on SCC.

Heat treatment. The heat treatment methods selected in this project include normalized (T1), thermomechanical rolled or thermomechanical formed (T2), and quenched and tempered (T3). However, since the heat treatment process is fixed for each pipeline steel grade, it is difficult to separate heat treatment as an independent variable when evaluating its effect on SCC.

pH. Analysis of field samples indicated that cracking is most frequently associated with a solution pH of approximately 6.5 beneath damaged coatings [17]. Although the measured pH values may deviate from the actual values present at the crack sites, they still serve as useful references. In addition to the investigation of near-neutral pH SCC, pH values of 9 and 10 were also selected to represent high-pH SCC conditions. Accordingly, 6.5 (pH1), 9.0 (pH2), 10.0 (pH3) are selected for this project to investigate the effect of pH on SCC.

Temperature. According to reference [18], the operating temperature range of main gas pipelines is typically between 25 °C and 60 °C during summer. Additionally, the typical temperatures downstream of compressor stations are often between 38 °C and 49 °C. This project will test three levels of temperature, which are 25 °C (TCA1), 38 °C (TCA2), and 50 °C (TCA3), to evaluate the influence of temperature on pipeline SCC. Room temperature is 25 °C, and higher temperatures (38 °C and 50 °C) are achieved and maintained using a heating blanket.

Pressure cycling. To investigate the effect of pressure cycling on pipeline SCC initiation, the specimens are submerged in a corrosive solution and periodically tested under cyclic loading. This approach is intended to replicate the combined effects of material defect, corrosion, and mechanical stress, which are key contributors to pipeline SCC development. Then, slow strain rate test (SSRT) will be conducted to evaluate the material's susceptibility to environmentally assisted cracking (EAC).

(1) Cyclic loading

The actual pressure cycling experienced by in-service pipelines exhibits time-dependent variations in both amplitude and frequency (**Fig. 1**). However, accurately replicating such complex pressure fluctuation patterns in a laboratory environment presents challenges. This research adopts constant-amplitude cyclic loading as an initial experimental approach, aiming to systematically evaluate the effects of loading amplitude and frequency on the susceptibility of pipeline to SCC. Both loading amplitude and frequency are intrinsically related to strain rate.

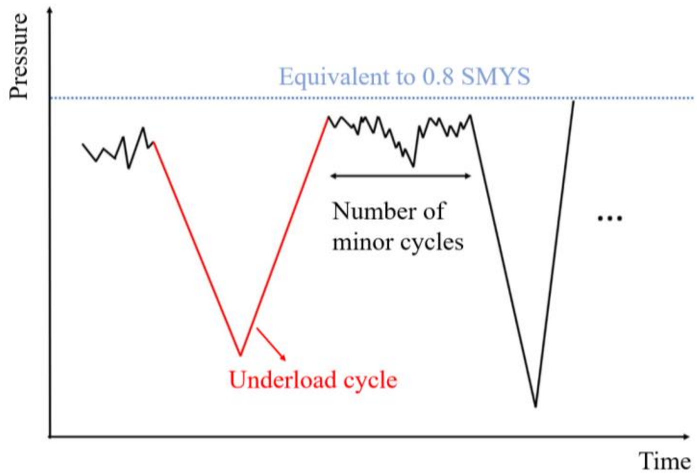

Fig. 1. Actual pressure cycling experienced by in-service pipelines [19].

According to B31.4 and B31.8 [20,21], the allowable stresses in pipelines are expressed as:

$$S = F \times E \times S_y \quad (1)$$

where S is the allowable stress; E is weld joint factor; F is design factor based on nominal wall thickness, typically equal to 0.72; and S_y is the SMYS of the pipe material.

Accordingly, the baseline pressure cycling amplitude (PCA1) is conservatively set at 0.8×SMYS, with PCA2 and PCA3 set at 0.7×SMYS and 0.9×SMYS, respectively. In addition, the loading frequency are selected based on the range recommended in reference [22]. As shown in **Table 3**, the range of loading frequencies is from 5.1×10^{-6} Hz to 0.01 Hz. Therefore, the pressure cycling frequency is initially set at 1×10^{-3} Hz for PCF1, 1×10^{-2} Hz for PCF2, and 1×10^{-4} Hz for PCF3, respectively. Since low-frequency loading limits the number of daily cycles, different daily loading cycles will be applied for each frequency, and nondestructive testing results will be used to evaluate the degradation of pipeline steel. The daily loading cycles for the SCC loading frequency experiment are shown in **Table 7**.

Table 3. Characteristics of underload-dominant pressure fluctuations in oil and gas pipelines [22]

Items	Oil pipelines	Gas pipelines
Numbers of underloading cycles per year	537	8
Range of loading frequency (Hz)	$5.1\times10^{-6} \sim 1.0\times10^{-2}$	$1.3\times10^{-6} \sim 5.3\times10^{-6}$
Range of unloading frequency (Hz)	$6.9\times10^{-6} \sim 1.0\times10^{-1}$	$1.3\times10^{-6} \sim 9.2\times10^{-5}$
Number of minor cycles between two adjacent underloads	0 ~ 26	0 ~ 37

(2) SSRT

After the cyclic loading under corrosion exposure, SSRT is conducted to evaluate the steel's susceptibility to EAC. The strain rate for SSRT is preliminary set at 1 με/s according to the recommendations of ASTM G129 [23] and ISO 7539-7 [24].

2.1.2 Specimen design

Small specimens are typically used in SCC mechanism studies and SSRT tests. However, since this project aims to address both pipeline SCC mechanisms and monitoring technology the specimen design must accommodate sensor installation while ensuring reliable SCC evaluation. ASTM E8 specifies standard tensile specimens (**Fig. 2**) for large-diameter tubular products, and noted that G/W should exceed 4 for accurate elongation measurements. Since elongation is a critical indicator for evaluating susceptibility in SSRT tests, selecting appropriate specimen geometry is essential to obtain valid results.

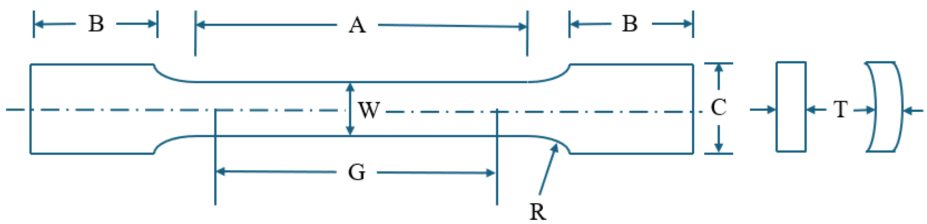

Fig. 2. Test specimens for large diameter tubular pipes [25].

Specimen dimensions are listed in **Table 4**. To ensure secure gripping during testing and minimize unnecessary exposure to the corrosive environment, the central section of the specimen will serve as the focus area for SCC evaluation, with the remaining sections protected during testing. The standards do not impose specific limitations on the specimen dimensions. As long as the specimens can be securely gripped in the loading equipment without affecting the stress distribution in the gauge area, the impact of specimen shape on experimental results will be minimal. Currently, each experimental set includes three specimens. We may further adjust the dimensions and quantity of specimens according to preliminary testing results.

Table 4. Dimensions of the specimen

Parameter	Symbol	Value
Gage length	G	100 mm
Width	W	20 mm
Thickness	T	TBD
Radius of fillet	R	25 mm
Length of grip section	A	120 mm
Length of grip section	B	75 mm
Width of grip section	C	25 mm

2.1.3. Solution preparation

Based on literature review, the preliminary preparation methods for the corrosion solutions are as follows:

Near neutral pH solution. Before the test, the solution needs to be purged with 5% CO_2 gas that was balanced with N_2 for a period of 2 hours to establish a near neutral pH environment. The composition of the NS4 solution, prepared using analytical-grade reagents and deionized water (pH = 7), is shown in **Table 5** [26,27].

Table 5. Chemical composition of NS_4 solution

Chemicals	KCl	$CaCl_2 \cdot 2H_2O$	$NaHCO_3$	$MgSO_4 \cdot 7H_2O$
Concentrations (mg/L)	122	181	483	131

High pH solution. References [19,28,29] recommended that a standard solution for high-pH SCC laboratory experiments consists of an aqueous solution containing 0.5 M Na_2CO_3 and 1 M $NaHCO_3$.

2.2 Test Procedure

- Laboratory Testing:

To investigate the effects of individual causal factors on the mechanism of SCC, the experimental procedures have been further refined in accordance with ASTM G129 [23] and ASTM E8/E8M [25]. Research variables, control variables, and specimen quantities have been explicitly defined to ensure the scientific rigor and reproducibility of the experimental process. Experimental groups have been established for each variable to enable clear identification of the effects of single-factor variations on SCC behavior, while other potential influencing factors are rigorously controlled to maintain data accuracy and comparability. This systematic experimental design aims to comprehensively clarify the roles of specific causal factors in SCC mechanisms and to generate reliable data for subsequent mechanistic analyses and model development.

1. Effect of pressure cycling on SCC

The design for testing the effect of constant amplitude loading on SCC is shown in **Table 6**. The experimental procedure is as follows:

(a) Since the specimen is not pre-cracked, the time instant when cracking initiates under corrosion and loading conditions are uncertain. Therefore, a preliminary test of corrosion and mechanical loading is necessary to determine the onset of cracking.

(b) Specimen preparation should ensure that the surface finishes meet the applicable standards. Test specimens must be degreased and cleaned prior to testing, and care should be taken to avoid contamination before the test. Gauge marks should be prepared to facilitate elongation measurements during SSRT. Weigh the specimen to obtain its initial weight. Measure the cross-sectional area of the specimen. Speckle patterns will be applied to the specimen surface, and digital image correlation (DIC) will be explored to observe crack development in the exposed corrosion area during cyclic loading. The feasibility of this approach depends on the ability of the speckle patterns to maintain their integrity in the corrosive environment, as they may become distorted or covered by corrosion products.

(c) The grip sections of the specimen are protected using epoxy resin or other suitable measures, leaving only the central gauge area exposed for subsequent immersion and cyclic loading. Simultaneously, AE sensors are installed for monitoring during the test. A simplified layout is shown in **Fig. 3**.

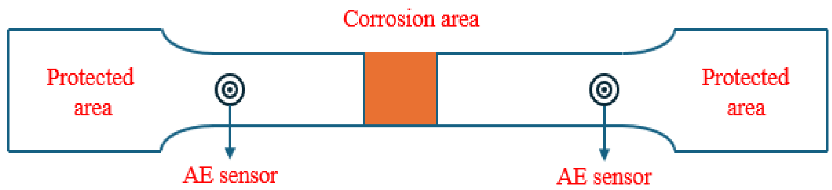

Fig. 3. Simplified layout of specimen and AE sensor positioning.

(d) The specimen is submerged in the corrosive solution and subsequently removed for post-exposure cyclic loading. It is loaded to the maximum stress amplitude and then unloaded. A set of experiments is designed to evaluate the effect of cyclic loading amplitude, frequency, and R on pipeline SCC. Relevant parameters are shown in **Table 6**. During the loading process, the DIC will be used to monitor the crack location, as well as the surface length and width of the cracks. The AE sensors are used to collect the cracking signal.

Table 6. Design for testing the effect of constant amplitude loading on SCC

Variables	Amplitudes	R	Frequency (Hz)	Number of specimens	Other parameters
None-corroded specimen for AE testing	0.8 × SMYS	0.5	1×10^{-3}	3	Steel grade: X52M Temperature: 25 °C Heat treatment: T2
Pressure cyclic amplitude	0.8 × SMYS	0.5	1×10^{-3}	3*	pH = 6.5 Steel grade: X52M Temperature: 25 °C Heat treatment: T2
	0.7 × SMYS			3	
	0.9 × SMYS			3	
Pressure cyclic frequency	0.8 × SMYS	0.5	1×10^{-2}	3	
			1×10^{-3}	3*	
			1×10^{-4}	3	
R	0.8 × SMYS	0.5	1×10^{-3}	3*	
		0.8		3	
		0.9		3	

Note: "*" denotes the control condition.

Multiple specimens are tested to evaluate the effect of loading frequency on pipeline SCC. Since low-frequency loading limits the number of daily cycles, the immersion time is adjusted accordingly. Different loading cycles are applied for each frequency, and nondestructive testing results is used to evaluate the degradation of pipeline steel. The immersion time and the cyclic loading frequency are the variables. The loading cycles and approximate immersion times in the corrosion solution are shown in **Table 7**. It remains unclear whether the corrosion products on the steel surface affect the performance of DIC techniques. If the presence of corrosion products compromises the accuracy of crack length and width measurements, it may be necessary to remove the corrosion products before conducting this loading and crack monitoring step.

Table 7. Daily loading cycles and time parameters for the SCC loading frequency experiment

Cyclic loading frequency (Hz)	Loading cycles per day	Time required for loading (hours)	Immersion times per day (hours)
1×10^{-2}	10	0.28	23.72
1×10^{-3}	5	1.39	22.61
1×10^{-4}	2	5.56	18.44

Note: The pressure cyclic amplitude is 0.8 × SMYS; and the R is 0.5.

(e) After the loading process, non-destructive testing techniques such as UT are used to measure crack depth.

(f) Repeat steps (d) and (e).

(g) Once the specimen has undergone a designated period of corrosion immersion and cyclic loading, SSRT will be conducted to evaluate the pipeline susceptibility to EAC. Simultaneously, AE sensors are employed to capture the signal associated with crack propagation. The duration of immersion and cyclic loading (T_1) will be determined based on the corrosion conditions and crack development observed during formal experiments.

(h) The specimens are cleaned, weighed, and examined to assess the pitting corrosion condition and distribution. Then, the specimens are sectioned for further analysis. SEM and micro-CT are performed to examine the fracture surface morphology and microstructural features to determine the crack propagation mode (e.g., intergranular or transgranular fracture, brittle or ductile fracture, and hydrogen embrittlement).

2. Effect of temperature on SCC

The design for testing the effect of temperature and temperature cycling on SCC is shown in **Table 8**. The experimental procedure is similar to that described in the procedure for studying the effect of pressure cycling on SCC, with adjustments made only to the immersion solution temperature as required.

Table 8. Design for testing the effect of temperature on SCC

<table>
<tr><th colspan="2">Variable</th><th>Number of specimens</th><th>Other parameters</th></tr>
<tr><td rowspan="3">Constant temperature</td><td>25 °C</td><td>3*</td><td rowspan="5">pH =6.5
Steel grade: X52M
Heat treatment: T2
Cyclic loading amplitude: 0.8 × SMYS
Cyclic loading frequency: 1 × 10^{-3}
R: 0.5</td></tr>
<tr><td>38 °C</td><td>3</td></tr>
<tr><td>50 °C</td><td>3</td></tr>
<tr><td rowspan="2">Cyclic temperature</td><td>Amp.: 25-50 °C</td><td rowspan="2">3</td></tr>
<tr><td>Period = 1 day</td></tr>
</table>

Note: "*" denotes the control condition which is the same as that in **Table 6**.

3. Effect of soil condition, steel grade, and weld method on SCC

The design for testing the effect of soil condition, steel grade, and welding method on SCC is shown in **Table 9**. The experimental procedure is similar to that described in the procedure for studying the effect of pressure cycling on SCC, with adjustments made as needed to the immersion solution pH or to the specific specimens used.

Table 9. Design for testing the effect of soil condition, steel grade, and heat treatment on SCC

<table>
<tr><th>Variable</th><th>pH</th><th>Steel grade</th><th>Heat treatment</th><th>Weld method</th><th>Number</th><th>Other parameters</th></tr>
<tr><td rowspan="3">Effects of pH</td><td>6.5</td><td rowspan="3">X52M</td><td rowspan="3">T2</td><td rowspan="3">W1</td><td>3*</td><td rowspan="8">Temperature: 25 °C
Cyclic loading amplitude: 0.8 × SMYS
Cyclic loading frequency: 1×10^{-3} Hz
R: 0.5</td></tr>
<tr><td>9.0</td><td>3</td></tr>
<tr><td>10.0</td><td>3</td></tr>
<tr><td rowspan="3">Effects of steel grade and heat treatment</td><td rowspan="3">6.5</td><td>X42</td><td>T1</td><td rowspan="3">W1</td><td>3</td></tr>
<tr><td>X52M</td><td>T2</td><td>3*</td></tr>
<tr><td>X65Q</td><td>T3</td><td>3</td></tr>
<tr><td rowspan="2">Effects of welding method</td><td rowspan="2">6.5</td><td rowspan="2">X52M</td><td rowspan="2">T2</td><td>W1</td><td>3*</td></tr>
<tr><td>W2</td><td>3</td></tr>
</table>

Note: "*" denotes the control condition which is the same as that in **Table 6** and **Table 8**. It should be noted that for the X52M steel, the W1 specimen was taken from the base metal area beyond ±90° from the seam weld.

4. Monitoring of the development of SCC using acoustic emission

This study aims to monitor the real-time development of SCC using AE techniques during the loading test. The sensors are attached to the specimen with corrosion products to capture transient elastic waves generated during crack initiation and propagation under mechanical loading. Throughout the entire loading process, AE signals are continuously recorded. By analyzing signal parameters such as amplitude, frequency, and energy, the progression of SCC can be tracked and characterized. The objective is to extract AE features indicative of different cracking stages, thereby enabling early detection and understanding of pipeline SCC behavior. The experimental procedure is as follows:

(a) Label each dog-bone specimen, record condition, especially the corrosion-loading cycle.

(b) Clean the surface to ensure good coupling between sensors and specimens.

(c) Attach two identical R15α sensors symmetrically on the surfaces of the shoulder regions at both ends of the specimen's gauge section.

(d) Evaluate the coupling quality and response consistency of AE monitoring system using the pencil lead break (PLB) method as a simulated signal source prior to formal testing.

(e) Determine the signal detection threshold based on the ambient noise level recorded under testing conditions.

(f) Monitor and record AE signals to capture crack initiation and propagation events in real time during the loading process.

(g) Analyze the recorded AE data to extract key parameters such as hits, amplitude, energy, and rising time.

5. Detecting SCC using ultrasonic testing

This study aims to differentiate the wave propagation characteristics among undamaged specimens, those with conventional tensile damage, and those with SCC. To understand the specific ultrasonic responses caused by SCC, the identical dog-bone samples that are simply broken by tensile fracture will also be detected. During the test, Lead Zirconate Titanate (PZT) transducers are first mounted on both ends of the specimen using cyanoacrylate adhesive before the corrosion process begins. The mounted transducers are then protected with corrosion-resistant materials such as heat shrink tubing. After each corrosion-loading cycle, UT is performed to determine whether cracks have initiated and to analyze the ultrasonic responses. By comparing the UT signal responses from three groups, including intact samples, the SCC-damaged samples, and the tensile-fractured samples, clear acoustic differences between different damages can help distinguish SCC from simple mechanical damages. The experimental procedure is as follows:

(a) Label each dog-bone specimen, record condition, especially the corrosion-loading cycle.

(b) Clean the surface to ensure good coupling between PZT and specimen.

(c) Attach the PZT transducers to the specimen using cyanoacrylate adhesive, assigning them as transmitter and receiver, respectively.

(d) Protect the PZT sensors using heat shrink tubing and anti-corrosion measures to prevent interference from the corrosion testing environment.

(e) Adjust instrument settings based on dispersion analysis.

(f) Pitch-catch will be used to detect the specimens.

(g) Acquire ultrasonic waveform data and analyze the key parameters.

- Field Testing: None

3. Results and Discussions

3.1. Task I: Comprehensive Review

- Task I.1: Review of Literature and Prior Research on SCC

Through reviewing previous research on SCC, including the mechanisms, causal factors, monitoring techniques, prediction methods, current challenges, and new opportunities. The results and discussions are summarized as follows:

(1) SCC propagation is governed by metallurgical properties, corrosive environments, and stress, with these factors often interacting in a coupled manner. Its time-dependent nature further complicates the underlying mechanisms.

(2) While extensive research has explored individual factors affecting SCC, studies on the combined effects of multiple variables remain limited. Current experimental methods face limitations in replicating real-world pipeline conditions, particularly in capturing SCC behavior under variable amplitude pressure fluctuations. This limitation is present not only in near-neutral pH environments, where research on the impact of variable pressure fluctuations on SCC progression remains limited, but is even more pronounced in high-pH environments, where such studies are scarce.

(3) Predicting crack growth rates remains a challenge due to the complex interplay between electrochemical reactions and mechanical responses induced by pressure fluctuations. Existing models, which are largely based on empirical data, require further improvement to better incorporate SCC development mechanisms and improve prediction accuracy.

(4) There is a need to develop an innovative monitoring technique for monitoring multi-scale pipeline SCC.
   - The comparison and evaluation of monitoring technologies shows that vision-based, sound wave-based, and electrical techniques focused more on the crack propagation while electrochemical techniques concentrated on the corrosion development.
   - UT was used to evaluate material conditions and construct 2D images for estimating the locations and morphology of cracks. Linear UT can be used for sizing macro-scale cracks, while nonlinear UT is effective in detecting micro-scale cracks. AE is highly sensitive to the evolution of SCC and has the potential of real-time detection.
   - Vision-based methods are the most direct and simplest techniques for monitoring SCC. Both DIC and Infrared Thermography (IRT) can be used to detect, locate, and quantify the crack. Images are constructed to characterize the state and morphology of the cracks. However, they are limited to detecting surface cracks.

- Electrical techniques can detect internal cracks but only applicable for conductive materials. Eddy Current Testing (ECT) is sensitive to surface, shallow crack. Direct Current Potential Drop (DCPD) can detect deep cracks and quantify the depth of cracks. However, accurate defect sizing remains challenging.
- Electrochemical techniques can detect the initiation of SCC. Both Electrochemical Noise (EN) and Electrochemical Impedance Spectroscopy (EIS) are sensitive to corrosion and early-stage SCC. However, due to limitations in specimen size and the need for a controlled testing environment, these methods are more suitable for laboratory testing rather than for practical applications.
- AI-powered data analysis can process large volumes of data, enhancing detection accuracy and prediction capabilities. However, AI techniques still require large datasets and on-site implementation. Robots help overcome the limitations of manual inspection, making SCC monitoring more efficient and accurate.

- <u>Task I.2: Review of Industry Standards and Practices</u>

Established standards such as ASME B31.4 (Pipeline Transportation Systems for Liquids and Slurries) [20] and ASME B31.8 (Gas Transmission and Distribution Piping Systems) [21] comprehensively address the design, materials, construction, inspection, corrosion control, operation, and maintenance of liquid and gas pipeline systems. Furthermore, specific guidelines for Stress Corrosion Cracking Direct Assessment (SCCDA) [30] provide systematic guidance, covering pre-assessment, data collection, maintenance decision-making, and the determination of appropriate inspection intervals. The SCCDA procedure is illustrated in **Fig. 4** [30].

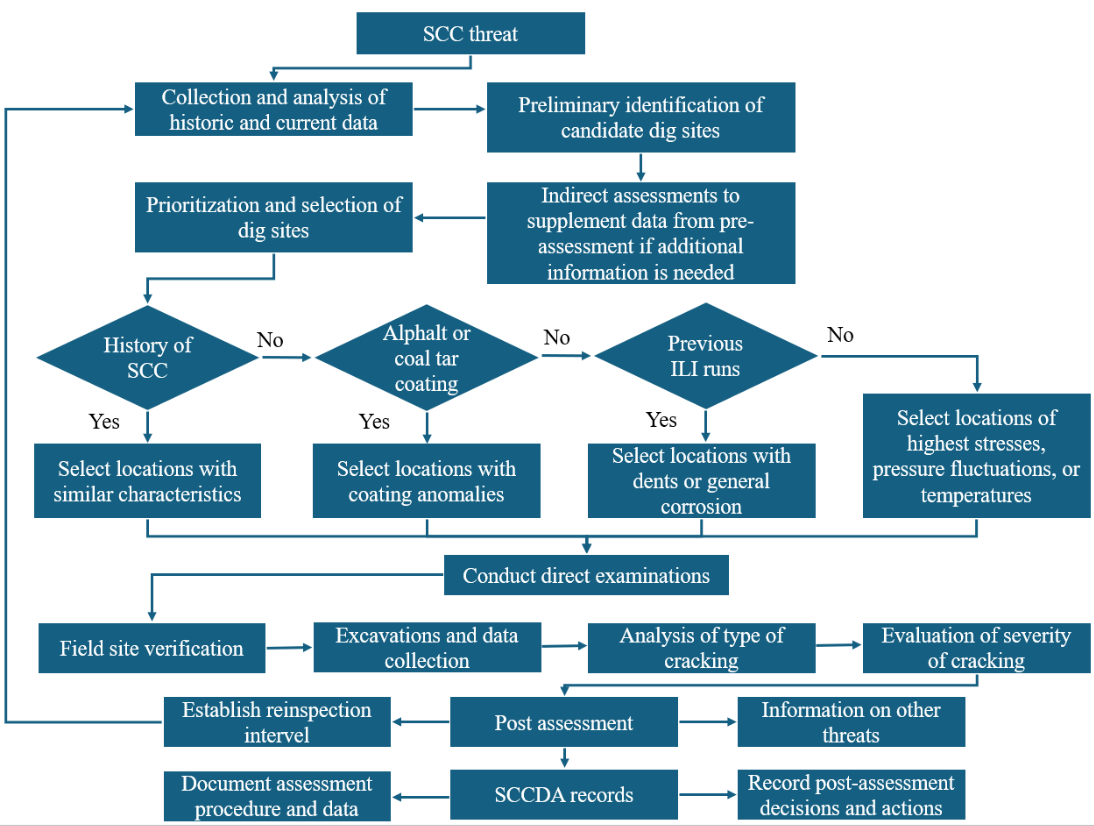

Fig. 4. Flow chart for SCCDA process [30].

3.2. Task Ⅱ: Investigation of Multiple Causal Factors of Pipeline SCC

- Task II.1: Effect of individual causal factors on pipeline SCC

Preliminary experiments were conducted to assess the feasibility of the formal experiment and to refine the experimental design accordingly. Through the preliminary tests and the analysis of the results, the experimental design was refined and improved, particularly in the aspects of sensor adhesive, monitoring system configuration, and optimization of the corrosion protection strategy. The key findings are as follows:

(1) The specimen with the longest immersion and five load cycles showed evident corrosion without cracking, suggesting that longer test durations are needed for the pipeline material under the present conditions.

(2) The present corrosion protection relies on epoxy, which is often compromised by gripping forces. A combined scheme was adopted to enhance durability. Epoxy is applied to surfaces that do not contact the grips and to encapsulate the ultrasonic transducer, while high-density adhesive tape is applied to specimen ends. The tape is removable, allowing repeated installation of AE sensors and providing clearance for clamping by the grips.

(3) The methods for sensor adhesion and fixture were finalized based on preliminary experiments. The AE sensors will be coupled to each end of the specimen using silicone grease as a couplant and then fixed in place with heavy-duty adhesive tape. The piezoelectric discs and patches required for the guided wave tests will be permanently bonded to the dog-bone specimen with a thin-layer cyanoacrylate adhesive and subsequently coated with an epoxy layer for corrosion protection.

(4) The configuration of the monitoring system was adopted based on experiments. The monitoring threshold of AE system was set to 35 dB. An active denoising algorithm, which integrates counts, peak counts, and energy, was implemented to filter out mechanical noise. The hit definition time was adjusted to a range of 200-400 μs to mitigate the impact of continuous noise on the measurement of signal, specifically energy and duration. Before each test, a cross-channel signal comparison will be performed to ensure consistent and effective sensor coupling and data acquisition.

4. Future work

In the next four quarters, we will conduct the following tasks:

(1) Continue formal experiments and collect data to investigate the effects of both individual and combined factors on the SCC process.

(2) Analyze the experimental results corresponding to each influencing factor and prepare a research paper based on the findings.

(3) Integrate experimental data with published research to obtain a deeper understanding of SCC mechanisms.

(4) Apply artificial intelligence techniques to develop predictive models for SCC crack propagation.

References

[1] Pipeline and Hazardous Materials Safety Administration (PHMAS). 2018. General pipeline FAQs. [online] Available at: https://www.phmsa.dot.gov/faqs/general-pipeline-faqs?utm_source=chatgpt.com#QA_6. [Accessed October 28, 2025]

[2] Pipeline and Hazardous Materials Safety Administration (PHMAS). 2024. Pipeline miles and facilities 2010+. [online] Available at: https://portalpublic.phmsa.dot.gov/analytics/saw.dll?PortalPages. [Accessed October 28, 2025]

[3] Pipeline and Hazardous Materials Safety Administration (PHMAS). 2024.Federal effort. [online] Available at: https://www.phmsa.dot.gov/pipeline/effort-allocation/federal-effort?utm_source=chatgpt.com. [Accessed October 28, 2025]

[4] Xiao, R., Zayed, T., Meguid, M.A. and Sushama, L., 2023. Understanding the factors and consequences of pipeline incidents: An analysis of gas transmission pipelines in the US. Engineering Failure Analysis, 152, p.107498.

[5] Cheng, Y.F., 2013. Stress corrosion cracking of pipelines. John Wiley & Sons.

[6] Song, F.M., 2010. Predicting the effect of soil seasonal change on stress corrosion cracking susceptibility of buried pipelines at high pH. corrosion, 66(9), pp.095004-095004.

[7] Jones, R.H., 2003. Stress-corrosion cracking. In Corrosion: fundamentals, testing, and protection (pp. 346-366). ASM international.

[8] Yu, M., 2015. Crack growth behavior of pipeline steels under variable pressure fluctuations in a near-neutral pH environment.

[9] Chen, W., 2017. Modeling and prediction of stress corrosion cracking of pipeline steels. Trends in oil and gas corrosion research and technologies, pp.707-748.

[10] Calabrese, L. and Proverbio, E., 2020. A review on the applications of acoustic emission technique in the study of stress corrosion cracking. Corrosion and Materials Degradation, 2(1), pp.1-30.

[11] Hernandez-Valle, F., Clough, A.R. and Edwards, R.S., 2014. Stress corrosion cracking detection using non-contact ultrasonic techniques. Corrosion Science, 78, pp.335-342.

[12] Parkins, R.N., 1980. Predictive approaches to stress corrosion cracking failure. Corrosion Science, 20(2), pp.147-166.

[13] Butusova, Y.N., Mishakin, V.V. and Kachanov, M., 2020. On monitoring the incubation stage of stress corrosion cracking in steel by the eddy current method. International Journal of Engineering Science, 148, p.103212.

[14] Bosch, R.W., 2005. Electrochemical impedance spectroscopy for the detection of stress corrosion cracks in aqueous corrosion systems at ambient and high temperature. Corrosion Science,

47(1), pp.125-143.

[15] Shahriari, A., Shahrabi, T. and Oskuie, A.A., 2013. A study on stress corrosion cracking of X70 pipeline steel in carbonate solution by EIS. Journal of materials engineering and performance, 22(5), pp.1459-1470.

[16] Abubakar, S.A., Mori, S. and Sumner, J., 2022. A review of factors affecting SCC initiation and propagation in pipeline carbon steels. Metals, 12(8), p.1397.

[17] Parkins, R.N., Blanchard, W.K. and Delanty, B.S., 1994. Transgranular stress corrosion cracking of high-pressure pipelines in contact with solutions of near neutral pH. Corrosion, 50(5), pp.394-408.

[18] Nazarova, M.N., Akhmetov, R.R. and Krainov, S.A., 2017, October. Temperature factors effect on occurrence of stress corrosion cracking of main gas pipeline. In IOP Conference Series: Earth and Environmental Science (Vol. 87, No. 6, p. 062011). IOP Publishing.

[19] Niazi, H., Chevil, K., Gamboa, E., Lamborn, L., Chen, W. and Zhang, H., 2020. Effects of loading spectra on high pH crack growth behavior of X65 pipeline steel. Corrosion, 76(6), pp.601-615.

[20] American Society of Mechanical Engineers (ASME), 2020. Pipeline transportation systems for liquids and slurries. ASME B31.4-2020. New York: ASME.

[21] American Society of Mechanical Engineers (ASME), 2020. Gas transmission and distribution piping systems. ASME B31.8-2020. New York: ASME.

[22] Zhao, J., Chevil, K., Yu, M., Been, J., Keane, S., Van Boven, G., Kania, R. and Chen, W., 2016. Statistical analysis on underload-type pipeline spectra. Journal of Pipeline Systems Engineering and Practice, 7(4), p.04016007.

[23] ASTM International, 2013. ASTM G129-00(2013): Standard practice for slow strain rate testing to evaluate the susceptibility of metallic materials to environmentally assisted cracking. West Conshohocken, PA: ASTM International.

[24] International Organization for Standardization (ISO), 2005. ISO 7539-7:2005 — Corrosion of metals and alloys — Stress corrosion testing — Part 7: Method for slow strain rate testing. Geneva: ISO.

[25] ASTM International, 2022. ASTM E8/E8M-22: Standard test methods for tension testing of metallic materials. West Conshohocken, PA: ASTM International.

[26] Luo, J., Luo, S., Li, L., Zhang, L., Wu, G. and Zhu, L., 2019. Stress corrosion cracking behavior of X90 pipeline steel and its weld joint at different applied potentials in near-neutral solutions. Natural Gas Industry B, 6(2), pp.138-144.

[27] Nking'wa, A.A. and Gao, K., 2024. Study on Stress Corrosion Cracking of X100 Pipeline Steel in NS4 Solution. Journal of Failure Analysis and Prevention, 24(4), pp.1934-1944.

[28] Niazi, H., Eadie, R., Chen, W. and Zhang, H., 2021. High pH stress corrosion cracking initiation and crack evolution in buried steel pipelines: A review. Engineering Failure Analysis, 120, p.105013.

[29] Lu, B.T., 2014. Further study on crack growth model of buried pipelines exposed to concentrated carbonate–bicarbonate solution. Engineering Fracture Mechanics, 131, pp.296-314.

[30] NACE International, 2008. NACE SP0204-2008: Stress corrosion cracking (SCC) direct assessment methodology. Houston, TX: NACE International.