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UNDERSTANDING WHY CRACKS FAIL - CAUSES OF CRACK FAILURES IN PIPELINES AND RESEARCH GAP ANALYSIS
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ABSTRACT
In 2021, the Pipeline Research Council International (PRCI) project MAT-8-3 was conducted to refine the scope of future crack-related research to be pursued by PRCI for oil and gas transmission pipelines. Industry reports were reviewed to document crack-related failures (leaks and ruptures), near misses (identified before failure), and false positives (identified anomalies that were shown to not be crack-related). The case data ranged from the 1940s to the present time, included occurrences at base metal, girth welds, long-seam welds and fittings. Many different linepipe steels were covered, including pipe diameters from 8 to 40 inches, wall thicknesses from 0.156 to 0.675 inches, steel grades ranging from API 5L Grade B to X70, with various long-seam weld types, and originating from more than 20 different manufacturers. Interviews were conducted with different pipeline operators to verbally provide feedback and receive their comments on any of the crack-related cases associated with their company. The data were then used in group discussions with subject matter experts specialized in the technical areas of crack susceptibility, inspection methodologies used to detect and size cracks, assessment and remediation of identified crack-like anomalies, and approaches to crack management. This paper describes the common root causes for crack-related pipeline cases and the prioritized research gaps that were identified in this PRCI study.

1. INTRODUCTION

Cracking-related pipeline failures in oil and gas pipelines have occurred as long as pipelines have been used. Although their rate of incidents per mile is low, the consequences of loss of containment events can sometimes be severe. It is the job of pipeline integrity specialists to analyze their systems and determine the most appropriate approach.

Cracking of pipelines is a complex problem, and various engineering activities are applied to manage system integrity; from determining the susceptibility to cracking, inspecting to detect, characterize, and size crack anomalies, assessing and repairing identified features, and managing system operations to minimize the likelihood of cracks growing to critical size and failure. Research provided by PRCI helps the industry assure the continued structural integrity of pipeline systems.

In March 2020, the Executive Assembly of PRCI approved Crack Management (CM) as a Strategic Research Priority (SRP). To help refine the scope of PRCI's crack-related research over the next few years, the MAT-8-3 project team of the Design, Materials, and Construction Technical Committee (DMC) Technical Committee issued a request for proposal "Understanding Why Cracks Fail". PRCI awarded the contract to Engineering Mechanics Corporation of Columbus, with its partner and primary subcontractor RSI Pipeline Solutions LLC to conduct the work. The project furthers the operators' ability to manage cracking in pipelines, as outlined in CM-SRP report "Pathway to Achieving Efficient and Effective Crack Management" [1], which gave nine (9) core priorities as follows:

- Priority 1 - Continuous Improvement of In-Line Inspection (ILI) Capabilities - Joint Industry Project (JIP)
- Priority 2 - Understanding Why Cracks Fail, and Expanded Sharing of Learnings
- Priority 3 - Material Property Database Development
- Priority 4 - Advanced Threat Management – Autogenous Weld Defects
- Priority 5 - Advanced Threat Management – Environmentally Assisted Cracking
- Priority 6 - NDE Qualification for ILI Validation
- Priority 7 - Technology Qualification for ILI Technologies and Service Providers
- Priority 8 - Acquisition of Real Pipeline Defects
- Priority 9 - Reliability Model Framework for Crack Assessment

This work was conducted under "Priority 2". It builds on prior work and procedures that appear promising for future implementation, by focusing on the areas and associated goals, referred to by PRCI as the "Four Pillars" of the crack management program, and shown in Figure 1. The crack management strategy aims to be both ***efficient*** by utilizing resources on the highest risk pipelines by cracking threat and avoid unnecessary excavations, and ***effective*** by mitigating the risk of crack failures to as-low-as-reasonably-practicable.

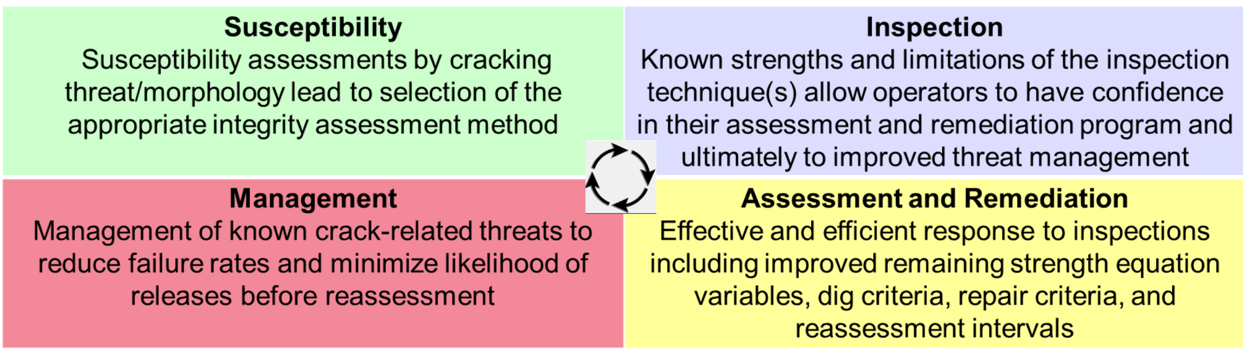


Figure 1 Illustration of Crack Management – Strategic Research Priority (CM-SRP).

2. OBJECTIVES

The objectives of this project were to detail the methodologies used to collect and review crack failures, near misses and false positives, and how the available technologies are used in consideration of the CM-SRP pillars of crack (1) susceptibility, (2) inspection, (3) assessment and remediation, and (4) management. Both past historical data as well as potential future integrity obstacles to navigate were to be addressed objectively with consideration of similar structural integrity evaluations in related industries.

3. SCOPE OF WORK AND APPROACH

The scope of work consisted of developing future research guideline suggestions through the following tasks:

- Task 1 - Collection and review of publicly available reports,
- Task 2 - Collection and review of PRCI member reports and operator interviews,
- Task 3 - Compilation of root causes for historic crack-related pipeline incidents,
- Task 4 - Categorization of root causes within the CM-SRP pillars, and
- Task 5 - Identification of research gaps in the CM-SRP.

This research identified trends in the incident direct causes and root causes. The collective information was used to identify gaps and opportunities for improvement.

4. RESULTS

The following gives an overview of the research distilled from the review, compilation, and categorization of the collected incidental reports that are publicly available and that were provided by PRCI members. In total, 128 historic crack-related pipeline cases were included, which represented occurrences in the period from 1961 through 2021. These were thought by the PRCI member companies interviewed to be representative and significant cases from their company's experience, and were not intended to include all service failure cases during this time period.

Table 1 lists the time of crack discovery and how the crack(s) appeared. It is noted that some of the cracks that were included in the dataset were found by ILI prior to failure by leak or rupture, and those were considered "near misses" for the purpose of this study.

Time of Crack Discovery	Crack Appearance						Total
	Explosion	Leak	Rupture	Surface Crack	Leak/Surface Crack	Unknown Appearance	
Unknown Discovery Time						4	4
During Excavation		2					2
During Manufacturing				1			1
During Repair	1						1
Gas Proof Test			1				1
Hydrostatic Test		2	8	2			12
In-Line Inspection		11		6			17
In-Service		29	60		1		90
Total	**1**	**44**	**69**	**9**	**1**	**4**	**128**

Table 1 Time of crack discovery and crack appearance, for the dataset of cases included in this study

4.1. Distribution of Aspects for Crack-Related Pipeline Cases in Dataset

Analysis of the dataset revealed the following historical distribution of crack-related pipeline cases:

- Cases:
    - Location on the pipe was 46% long-seam weld, 37% base metal and/or fitting, 12% girth weld, 2% fitting only, and 3% unknown or not reported
- Failure modes:
    - Appearance at discovery was 54% ruptures, 34% leaks, 7% surface flaw, 1% surface flaw that started leaking, 1% explosion, 3% unknown or not reported
- Cracking incidents by fluid type:
    - Cracks: 68% on liquids lines, 28% on gas lines, 4% unknown or not reported
- Leaks and ruptures by fluid type:
    - Leaks: 74% on liquid lines, 26% on gas lines
    - Ruptures: 67% on liquid lines, 33% on gas lines

Table 2 summarizes the counts of the fluid contained in the pipeline (either gas or hazardous liquid) versus the crack appearance at the time of discovery.

Fluid	Crack Appearance						Total
	Explosion	Leak	Rupture	Surface Crack	Leak/Surface Crack	Unknown Appearance	
Unknown Fluid		2	2	1			**5**
Liquid	1	31	45	6		4	**87**
Gas		11	22	2	1		**36**
Total	**1**	**44**	**69**	**9**	**1**	**4**	**128**

Table 2 Fluid and crack appearance, for the dataset of cases included in this study

To compare the above numbers on a relative scale, the installed pipeline mileage in the U.S. in 2020 as reported by operators in their annual reports [2] to United States Department of Transportation (U.S. DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA) was as follows:

- Hazardous liquid or carbon dioxide transportation systems: 229,567 miles total
- Gas transmission systems: 301,622 miles total

Thus, hazardous liquids pipelines are approximately 2.7X more susceptible to crack-related rupture and approximately 3.7X more susceptible to crack-related leaks than gas pipelines.

Based on the data analysis, the following factors were found to DO influence cracking of pipelines:

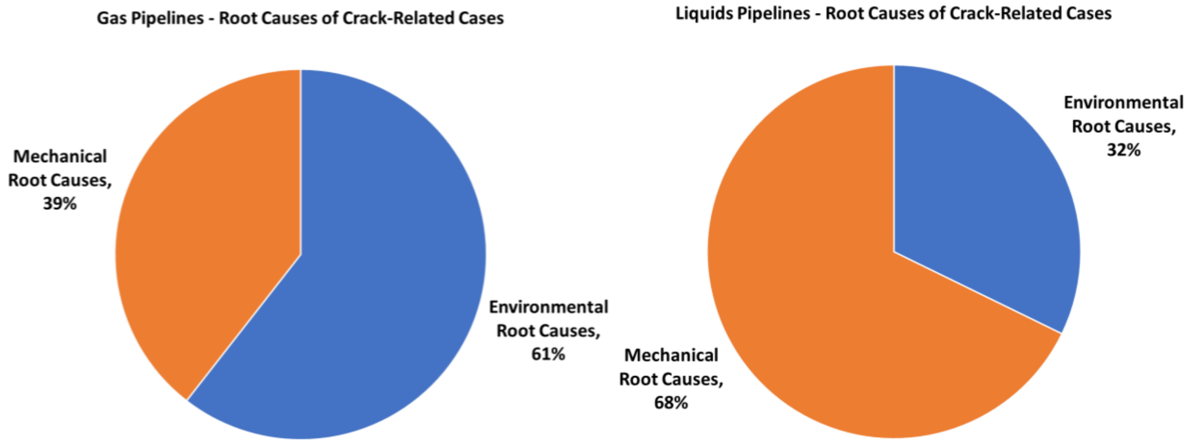
- The data after normalizing by installed mileage reveal that pipelines with diameters larger than 22 inches are more prone to crack-related failure than smaller diameter pipelines.
- AO Smith FW seam pipe and Youngstown Sheet and Tube ERW seam pipe have increased susceptibility to crack-related failures compared with other pipe manufacturers and other LSW types.

However, it COULD NOT be concluded that following aspects influence cracking:

- The data do not reveal that a particular combination of diameter (D) and wall thickness (t) or diameter-to-thickness (D/t) of pipe would be more susceptible to cracking than another combination.
- The data do not reveal that a particular combination diameter and steel grade of pipe would be more susceptible to cracking than another combination.
- The data do not reveal that line pipe with a particular combination of diameter and LSW type would be more susceptible to cracking than another combination.

4.2. Direct causes - Organized by cracking mechanism and location on pipe

In the following figures, some of the results of the analysis of incidents reported in the database from direct causes are presented graphically. The reader is referred to the 2021 PRCI MAT-8-3 report [3] for detailed discussion. Figure 2 (a) and (b) shows the relative proportion of environmental and mechanical root causes for gas and liquids lines, respectively. Figure 3 and Figure 4 provide the distribution of the underlying metallurgical and operations mechanisms for gas pipelines; again shown for environmental and mechanical causes, respectively. Figure 5 and Figure 6 show similar data for Liquids Pipelines. Figure 7 details underlying causes for long-seam weld failures on liquids pipelines.



(a) (b)

Figure 2 Crack-related failures by cause in (a) gas lines and (b) liquids lines

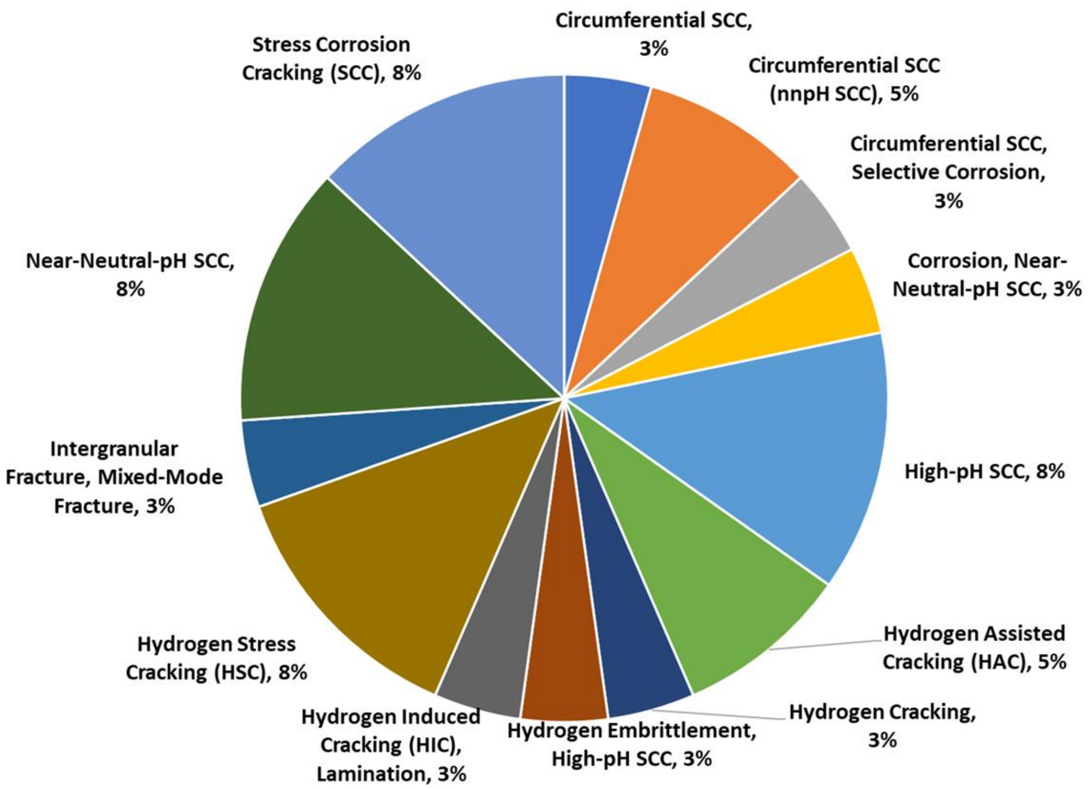


Figure 3 Gas pipelines – environmental root causes of crack-related cases

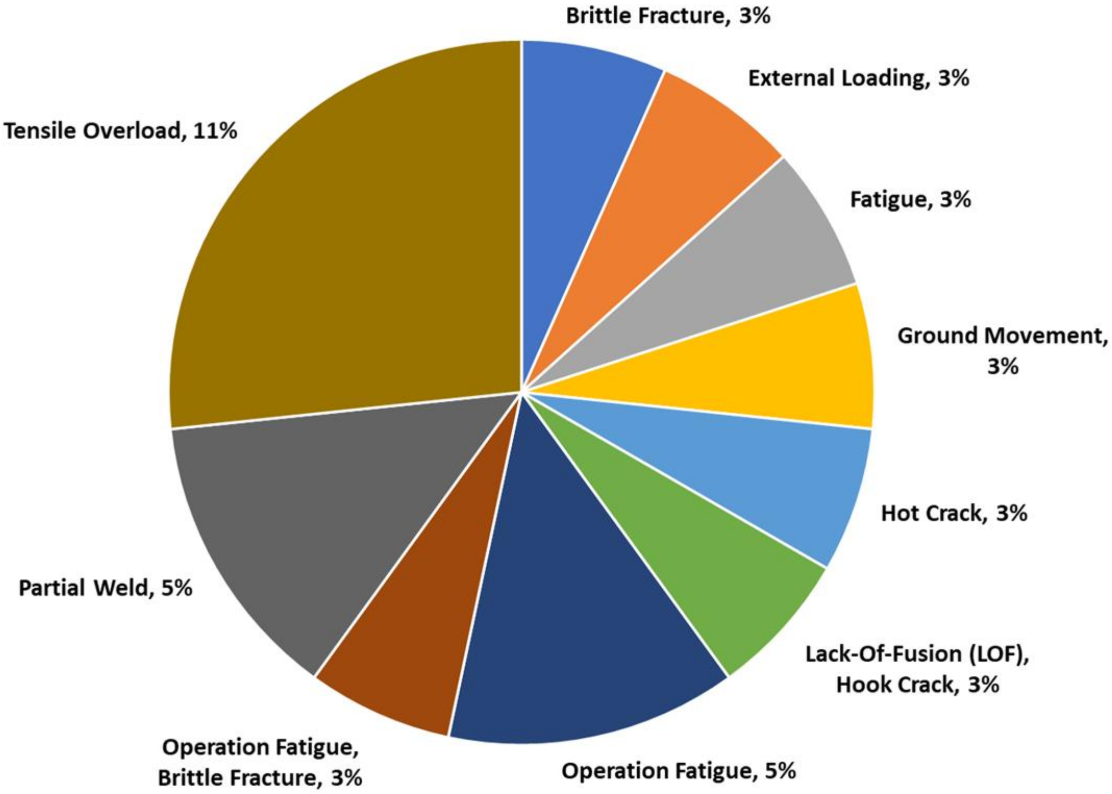


Figure 4 Gas pipelines – mechanical root causes of crack-related cases

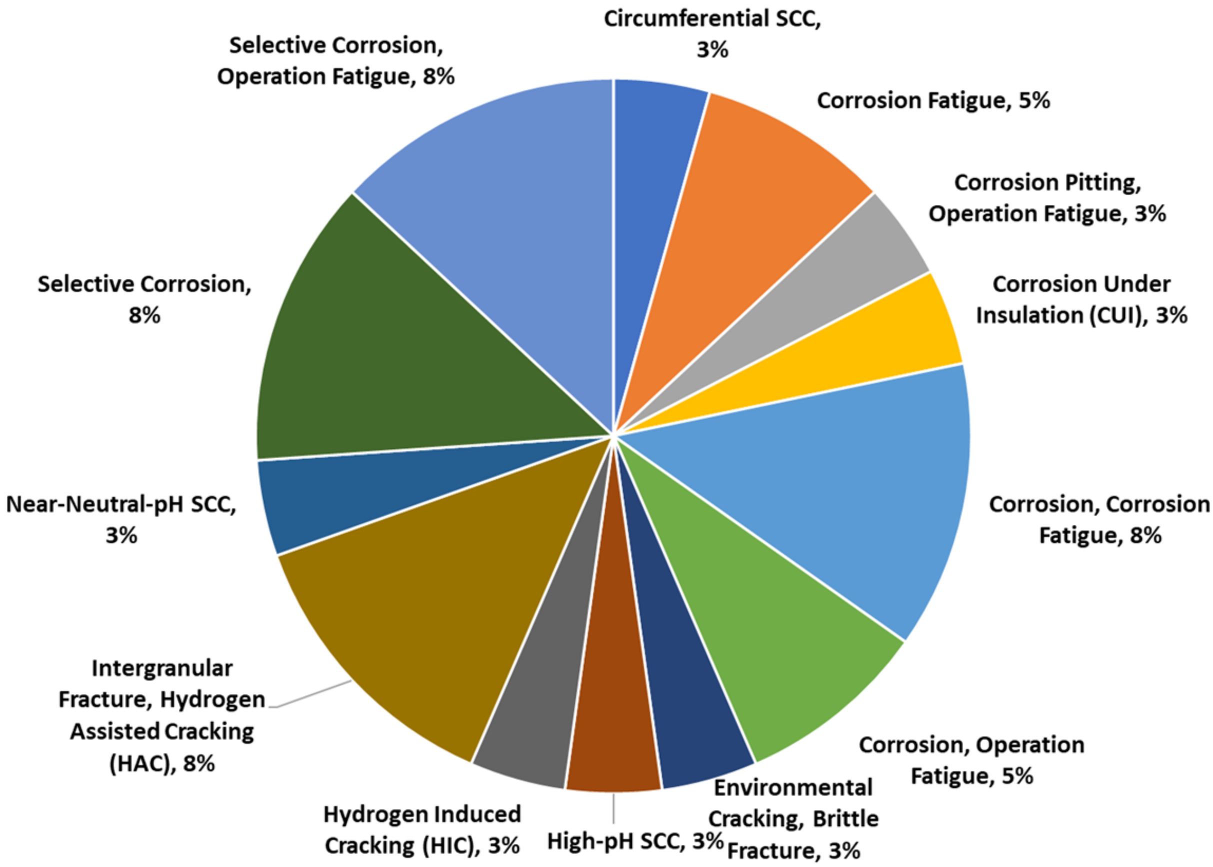


Figure 5 Liquids pipelines – environmental root causes of crack-related cases

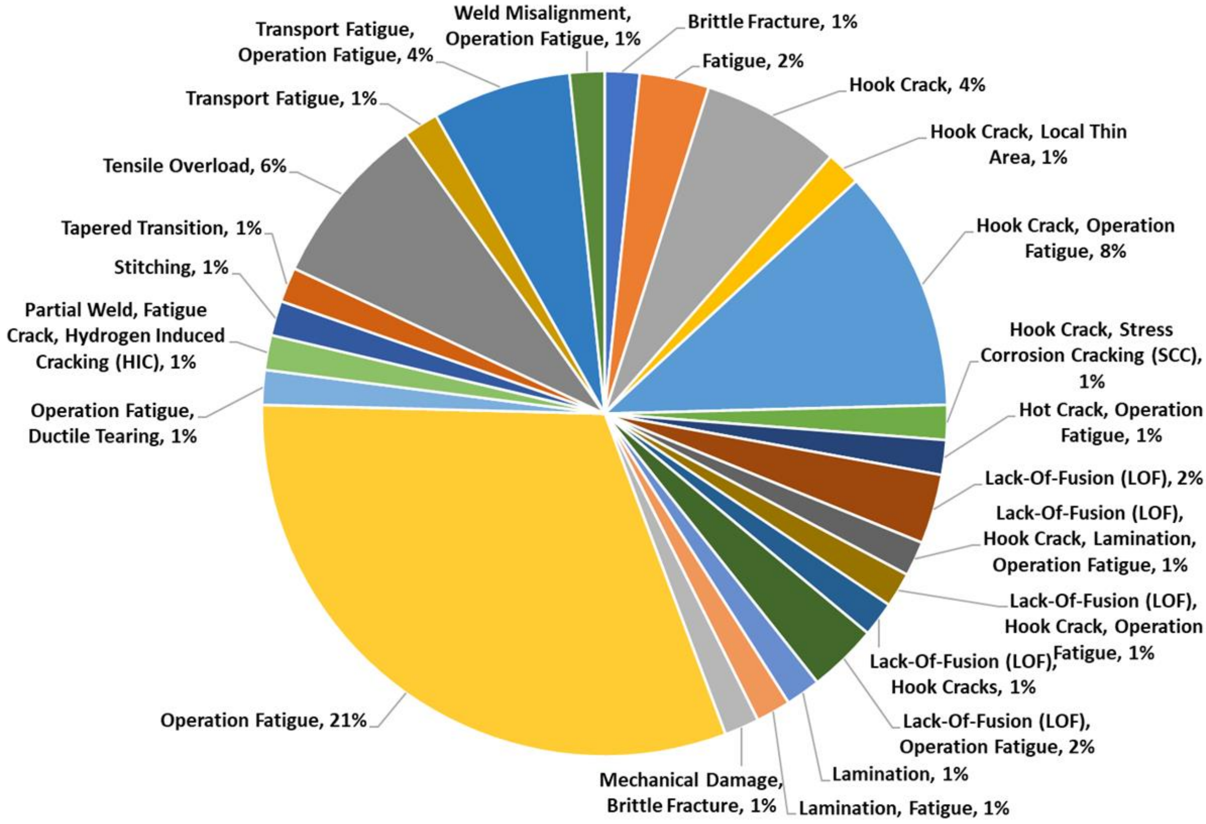


Figure 6 Liquids pipelines – mechanical root causes of crack-related cases

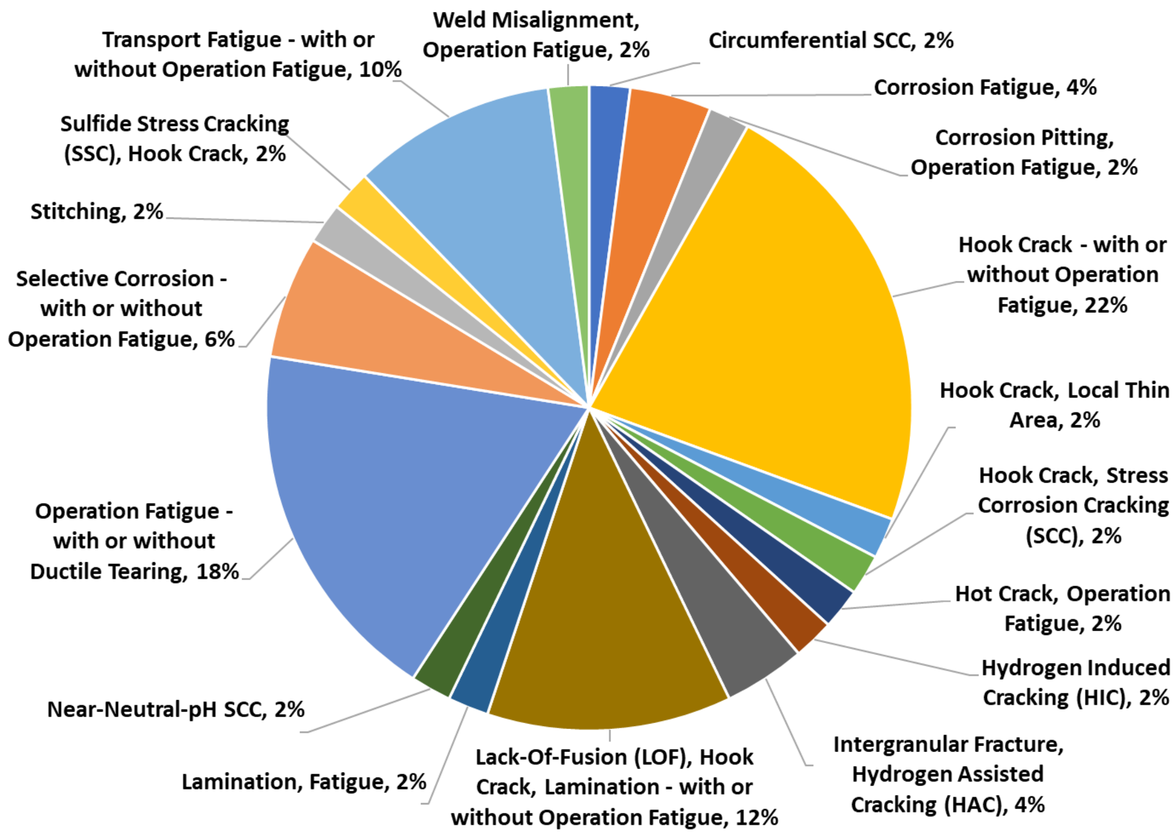


Figure 7 Liquids pipelines – long-seam weld root causes of crack-related cases

4.3. Root causes - Organized by the four CM-SRP pillars

In this section, the overall results of the analysis of root causes from the dataset collected in this project are presented. Table 3 provides a summary of the root causes identified in the historic crack-related pipeline cases of this study, organized by the four CM-SRP pillars.

The number of times that each root cause was determined is listed, and used for sorting by frequency of occurrence. The results were as follows:

- Cracking susceptibility 82 times
- Crack inspections 20 times
- Crack assessment and remediation 11 times
- Crack management 55 times

Thus, strictly considering the historic incident root causes, the recommended order of priority for future research to prevent crack-related failures is: 1. Susceptibility, 2. Management, 3. Inspections, 4. Assessment and Remediation.

The root causes of cracking failures are most often (82 times) related to the pipeline's susceptibility to cracking mechanisms.

When susceptibility was involved in crack-related failures, *operational fatigue* was the leading root cause of the incident.

In many cases (55 times), management activities play a role in the occurrence of cracks or precursor features, the initiation and/or continued growth of cracks, or the non-detection of cracks.

When crack management was involved in crack-related failures, the *unawareness of the severity of manufacturing defects* in new line pipe was identified as the leading root cause of the incident.

Crack inspections were less frequently (20 times) identified as the root cause of a failure, but sometimes inspections were included as a contributing factor. The number of ILI-related cases is relatively small in the dataset, and in practice thousands of features are assessed and remediated prior to failure and therefore not further reported.

When crack inspections were involved in crack-related failures, the leading root cause of the incident was related to the *misinterpretation of ILI signals*, which usually was related to a feature identification by the ILI vendor and the subsequent assessment of and response to that feature by the pipeline owner or operator.

Crack assessment and repair was identified as a root cause in only a few (11 times) failures.

When crack assessment and repair were involved in crack-related failures, *applied repairs that later failed* were identified as the leading root cause of the incident.

#	Cracking Susceptibility	#	Crack Inspections	#	Crack Assessment and Remediation	#	Crack Management
28	Factors made pipe susceptible to operational fatigue cracking	6	ILI issue - signals misinterpreted	4	Repair did not perform as planned	13	Unaware of severity of manufacturing defects in new line pipe
10	Factors made pipe susceptible to HAC or HIC	4	Hydrostatic test issue - cracks initiated or grew	2	Issues with data quality	10	Unaware of construction damage
10	Factors made pipeline susceptible to nnpH SCC	3	ILI issue - weld geometry	2	Issues with calculation inputs	8	Inadequate integrity management (IM) program
6	Factors made pipe susceptible to selective corrosion	2	ILI issue - feature depth and length	1	Lack of well-developed assessment model	5	Not running crack ILI tool
4	Manufacturing features in pre-1970 LF-ERW pipe made pipe weld bond line and HAZ susceptible to failure, e.g., from pressure-induced fatigue	1	ILI issue - lack of detection and sizing of feature that later failed	1	Assessment missed including important factor	4	Unaware of transportation damage to new line pipe
4	Factors made pipe susceptible to transportation fatigue	1	ILI issue - feature not characterized effectively	1	No assessment performed for crack-like feature (wrong defect type)	4	Issue with specifications
4	Factors made pipe susceptible to high-pH SCC	1	Hydrostatic test issue - hydrostatic test not very effective for high toughness pipe			3	Issue with operational management
3	Factors made pipe susceptible to corrosion fatigue	1	ILI issue - threat not recognized			1	Procedure not followed
3	Factors made pipe susceptible to C-SCC; nnpH SCC mechanism	1	Field-NDE issue - inadequate technique to detect crack in weld joint design			1	Inspection result not acted upon
2	Tenting of tape coating on DSAW pipe allowed ingress of corrosive environment, making pipe susceptible to grooving corrosion, corrosion fatigue					1	Issue with regulations

#	Cracking Susceptibility	#	Crack Inspections	#	Crack Assessment and Remediation	#	Crack Management
2	Excessive axial loading made pipe GW susceptible to cracking					1	Third party damage occurred
2	Factors made pipe susceptible to HSC					1	Unaware of third party damage
1	Multiple coinciding flaws made pipe more susceptible to failure					1	Insufficient follow-up resulted in repeat of failure mechanism
1	Manufacturing features in DSAW pipe made pipe weld bond line and HAZ susceptible to failure, e.g., from pressure-induced fatigue					1	Operator misinformed about susceptibility to cracking
1	Factors made pipe susceptible to internal SCC					1	Did not perform commissioning hydrostatic test
1	Absence of support made flange weld susceptible to cracking						
82	**TOTAL**	**20**	**TOTAL**	**11**	**TOTAL**	**55**	**TOTAL**

Table 3 Summary of high level root causes as determined from the historic cases included in this project, with count of how many times the root cause occurred, and categorized within the four CM-SRP pillars

5. CRACK MANAGEMENT

Pipeline integrity management as it relates to cracks is a complex topic, in which professionals aim for safe operations by taking action based on the understanding they develop from evaluating and integrating large amounts of information in a variety of categories. Based on the available data and the assessment of risks, decisions are made for maintenance and repairs. Figure 8 illustrates the crack assessment process, in which any activity affects the outcomes of subsequent activities. If any activities are executed poorly, or if critical information and/or data are unavailable, the process can break down and may result in incorrect assessments.

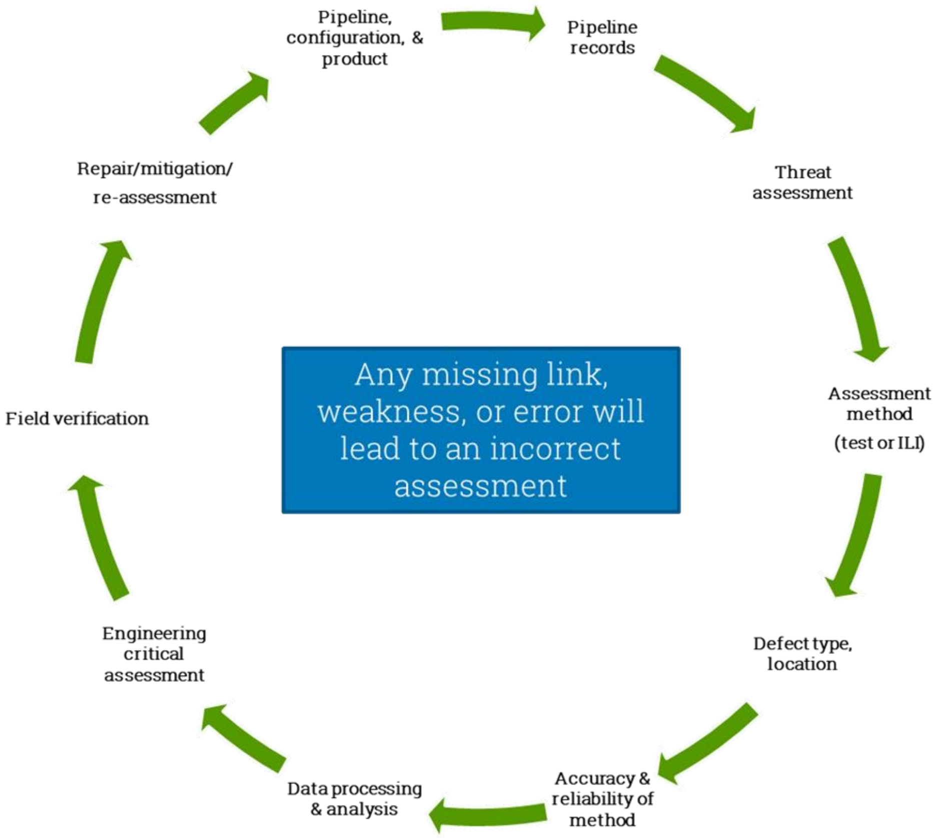


Figure 8 The crack assessment process

Next, research suggestions for future PRCI projects are provided, based on the identified gaps from the historic crack-related failure cases, operator interviews, and SME opinions about past and future developments.

6. RESEARCH SUGGESTIONS BASED ON GAP ANALYSIS

The work described here aims to enhance crack management by providing an independent review and understanding of the research gaps as they relate to cracking in pipelines, based on historic incidents, operator interviews, and SME opinions. PRCI members can use the future research guideline suggestions described in this report to allocate resources within the CM-SRP pillars.

The following is a summary listing of the prioritized research suggestions for the CM-SRP.

- Research Gaps in Cracking Susceptibility;
    - Improve cracking threat assessment methodologies,
    - Perform research to better understand and explore methods to minimize the threat of operational fatigue cracking,

- Perform research to better understand and explore methods to minimize the threat of HAC in vintage pipelines,
  - Perform research to establish crack growth rates for stress corrosion cracking,
  - Perform research to update crack interaction rules for stress corrosion cracking,
  - Perform research to determine threshold for crack initiation at selective corrosion,
  - Define what data to collect for a pipeline to determine susceptibility to specific cracking mechanisms,
  - Establish state-of-the-art of existing knowledge about the mechanical behavior of linepipe steels exposed to hydrogen environments to enable conversion of vintage pipelines for hydrogen transport, and
  - Develop ILI methods that can non-destructively estimate material properties.

- Research Gaps in Inspections for Cracks;
  - Develop standard for descriptive terminology for crack-like anomalies,
  - Investigate detrimental versus beneficial effects of hydrostatic testing for liquids pipelines,
  - Investigate detrimental versus beneficial effects of hydrostatic testing for pre-qualifying a pipeline for pure or blended hydrogen service,
  - Collect and manufacture ILI test spools specifically for validation of tools for cracks at welds,
  - Investigate benefits of running multiple different crack detection ILI technologies in the same pipeline,
  - Investigate benefits of multiple runs of the same crack detection ILI tool in the same pipeline,
  - Provide training about line pipe features for field-NDE inspectors and ILI analysts, and
  - Develop an NDE database.

- Research Gaps in Assessment and Remediation of Cracks;
  - Update the PRCI Pipeline Repair Manual,
  - Investigate influence of data quality and data uncertainties on assessment results,
  - Improve crack-growth-rate data for operational fatigue assessment,
  - Improve modeling of operational fatigue for complicated crack configurations,
  - Perform testing and update the fracture initiation transition temperature master curve model for newer line pipe steels, and
  - Continue improving crack assessment models for girth welds.

- Research Gaps in Crack Management;
  - Make PRCI research more easily available among PRCI members,
  - Make PRCI research results available beyond PRCI members,
  - Develop standard QA/QC procedures for procurement of new line pipe,
  - Collect and manufacture ILI test spools specifically for validation of tools for cracks coinciding with other damage, and
  - Develop a crack-specific guideline for integrity management programs.

7. REFERENCES

1. *Pathway to Achieving Efficient and Effective Crack Management*, Pipeline Research Council International (PRCI), 2020.
2. https://www.phmsa.dot.gov/data-and-statistics/pipeline/annual-report-mileage-summary-statistics, U.S. Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA).
3. *Causes of Crack Failures in Pipelines and Research Gap Analysis*, Catalog No. PR-276-241503-R01, February 25, 2021.