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Findings from PRCI Project MAT-8-3 "Understanding Why Cracks Fail" Causes of Crack Failures in Pipelines and Research Gap Analysis

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Introduction

- PRCI project MAT-8-3 "Understanding Why Cracks Fail"
  - Executed for Crack Management (CM) Strategic Research Priority (SRP)
  - Purpose: identify recommendations for future research efforts for CM-SRP
- Contractor was Engineering Mechanics Corporation of Columbus (Emc^2), with its partner and primary subcontractor RSI Pipeline Solutions LLC (RSI)
  - Principal Investigators/Technical Leaders: Michiel Brongers/Mike Rosenfeld/Gery Wilkowski
  - PRCI Project Team Leader: David Whaley
  - PRCI Project Manager: Thomas Marlow
  - Key PRCI member contributors: Taylor Shie (Shell), Sean Keane (Enbridge)
- Final Report, PRCI Catalog No. PR-276-241503-R01, "Causes of Crack Failures in Pipelines and Research Gap Analysis," February 2022

Problem Statement

- Cracking-related pipeline failures in oil and gas pipelines have occurred as long as pipelines have been used.
- Need to identify gaps in operators' knowledge, tools, and processes for recognizing and responding to cracking-related integrity threats in a timely manner.
- Need for operators to be more aligned in crack management strategies, because one failure reflects on the entire industry.

Objectives

- To assess the methodologies used to collect and review; crack failures, near misses and false positives, and how the available technologies are used, the following four CM-SRP pillars were followed:
  - Susceptibility to cracking,
  - Inspection for cracks,
  - Assessment and Remediation of crack-like features, and
  - Management of crack concerns.

- This assessment incorporated; an independent review of historic incidents, operator interviews, and subject matter expert (SME) opinions.

Scope of Work

- Task 1 – Collection and review of available reports
  - PRCI prior reports, public reports
- Task 2 – Collection and review of PRCI member incident reports and operator interviews
  - PRCI member reports, confidential reports
  - 16 operator interviews
- Task 3 – Compilation of root causes for historic crack-related pipeline incidents
  - 128 crack-related failure cases
  - 4 SME panel workshops (14 experts)
- Task 4 – Categorization of root causes within the CM-SRP
- Task 5 – Identification of research gaps in the CM-SRP

Background

- Results from this work are research suggestions as related to crack management
- Research suggestions were cross-referenced with core priorities outlined in CM-SRP report “Pathway to Achieving Efficient and Effective Crack Management”
- The research suggestions from present work were compared with future research project ideas that were previously submitted to PRCI

The Crack Assessment Process

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Pipeline configuration & product → Pipeline records → Threat assessment → Assessment method (test or ILI) → Defect type, location → Accuracy & reliability method → Data processing & analysis → Engineering critical assessments → Field verification → Repair/mitigation/re-assessment → Pipeline configuration & product

Any missing link, weakness, or error will lead to an incorrect assessment

Database of Crack-Related Failures from Members

- Recent historical distribution of crack-related failures from member cases supplied
  - Crack Location:
    - 46% long-seam weld, 37% base metal and/or fitting, 12% girth weld, 2% fitting only, and 3% unknown or not reported
  - Failure modes:
    - 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:
    - 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

Crack-Related Failures: Fluid Type and Crack Appearance

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**

- Normalizing data by installed mileage in the U.S. (DOT/PHMSA operator reports for 2019):
  - Hazardous Liquid or Carbon Dioxide Transportation Systems: 229,567 miles
  - Gas Transmission Systems: 301,622 miles
- *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.*

Crack-Related Failures: Pipe Grade and Diameter

Steel Grade	Diameter (inches)																	Total
	8.625	10.75	12.75	14	16	18	20	22	24	26	28	30	32	34	36	40	Unknown Diameter	
Unknown Grade	1							1								1	5	**8**
Grade B		2	2		1		1	1						1				**8**
Grade C		1																**1**
X42	4	3	3	1			1					1						**13**
X45*			1															**1**
X46	2	3	3		1		3	7										**19**
X52		1	4		2	1	3	6	8	8	1	6	1	11	3			**55**
X60			1		1				3	1		1				1	1	**9**
X65						1	1							3				**5**
X70									3			5						**8**
ASTM A27 Cast Steel, X70					1													**1**
Total	**7**	**10**	**14**	**1**	**6**	**2**	**9**	**15**	**14**	**9**	**1**	**13**	**1**	**15**	**3**	**2**	**6**	**128**

* Note: one steel was listed as having a specified minimum yield strength (SMYS) of 45,000 psi (X45) which was likely negotiated by the purchaser and manufacturer and not actually an 'X' grade.

Crack-Related Failures: Pipe Grade and Diameter

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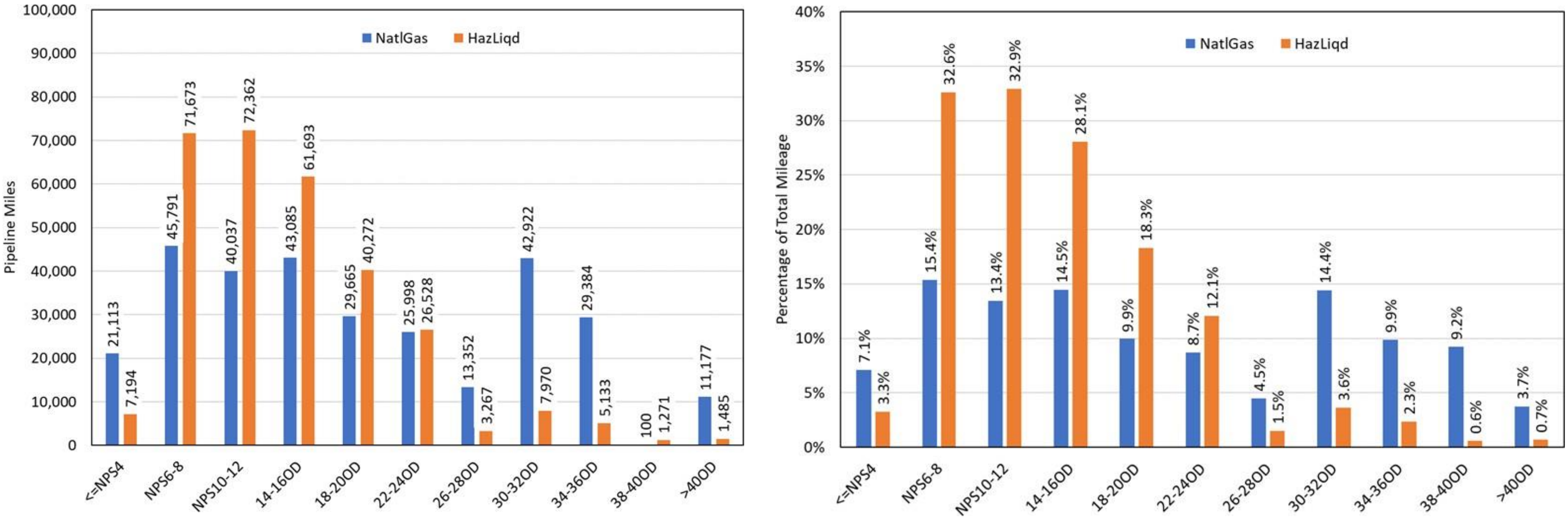

- The data after normalizing by installed mileage reveal that ***natural gas pipelines with diameters larger than 22 inches are more prone to crack-related failure than smaller diameter pipelines***.

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Crack-Related Failures: Location on Pipe and Weld Type

Crack Location In Pipe	Long-Seam Weld										Total
	dc-ERW	DSAW	ERW	FW	Helical DSAW	HF-ERW	LF-ERW	Seam-less	SSAW	Unknown Seam	
Unknown Location			1							3	**4**
Base Metal		14	6	10	1	3	1	5	1	6	**47**
Base Metal, Fitting						1					**1**
Fitting		1								1	**2**
GW		1		3						1	**5**
GW, Base Metal			2	2		1				1	**6**
GW, Fitting					1			1		2	**4**
LSW	5	13	8	7		7	12			1	**53**
LSW, Base Metal	2						1		1	1	**5**
LSW, GW				1							**1**
Total	**7**	**29**	**17**	**23**	**2**	**12**	**14**	**6**	**2**	**16**	**128**

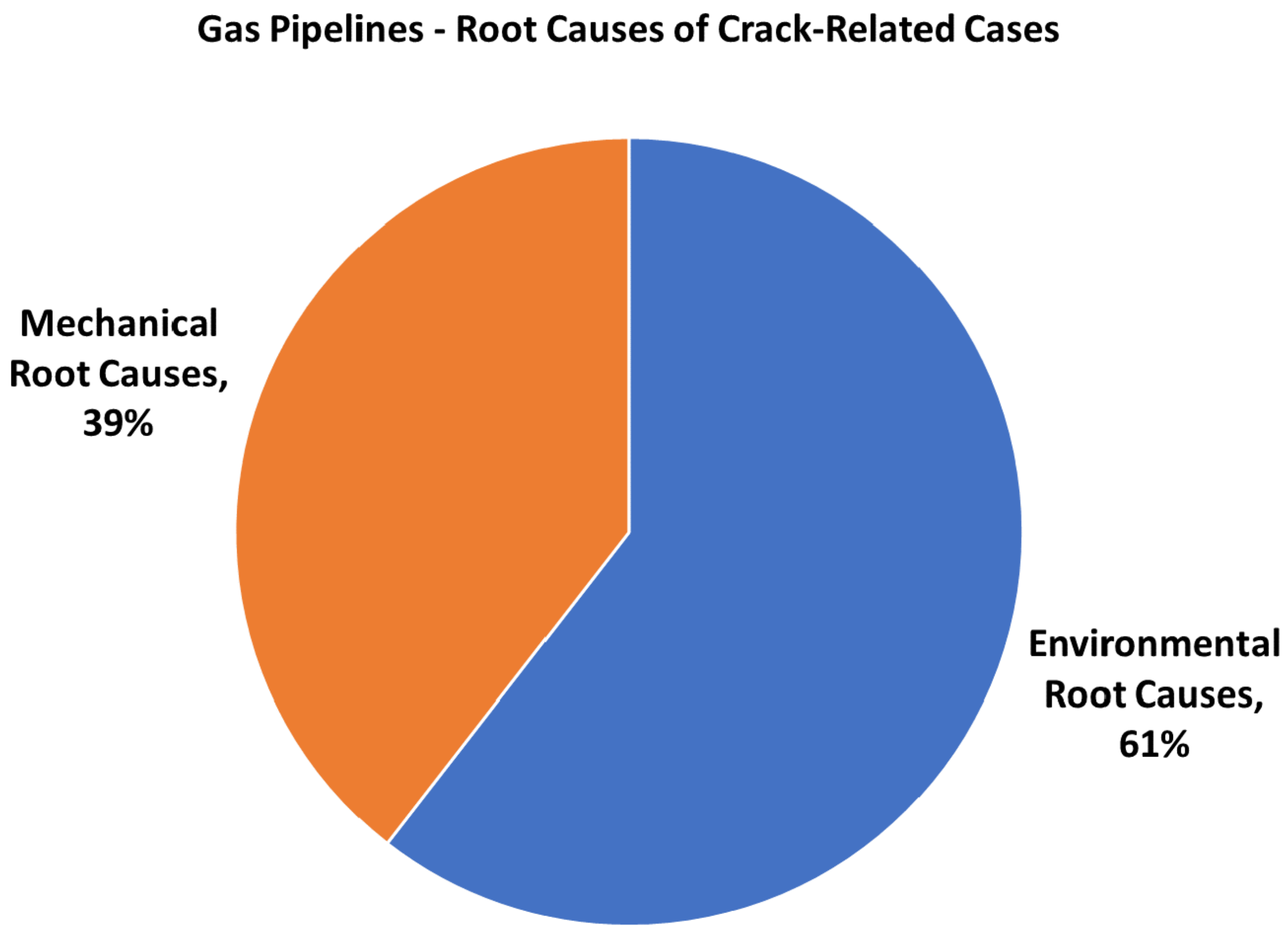
- The data *after normalizing by mileage show that AO Smith FW and Youngstown Sheet & Tube ERW seam pipe have increased susceptibility to crack-related failures* compared with other pipe manufacturers and other long-seam weld types.

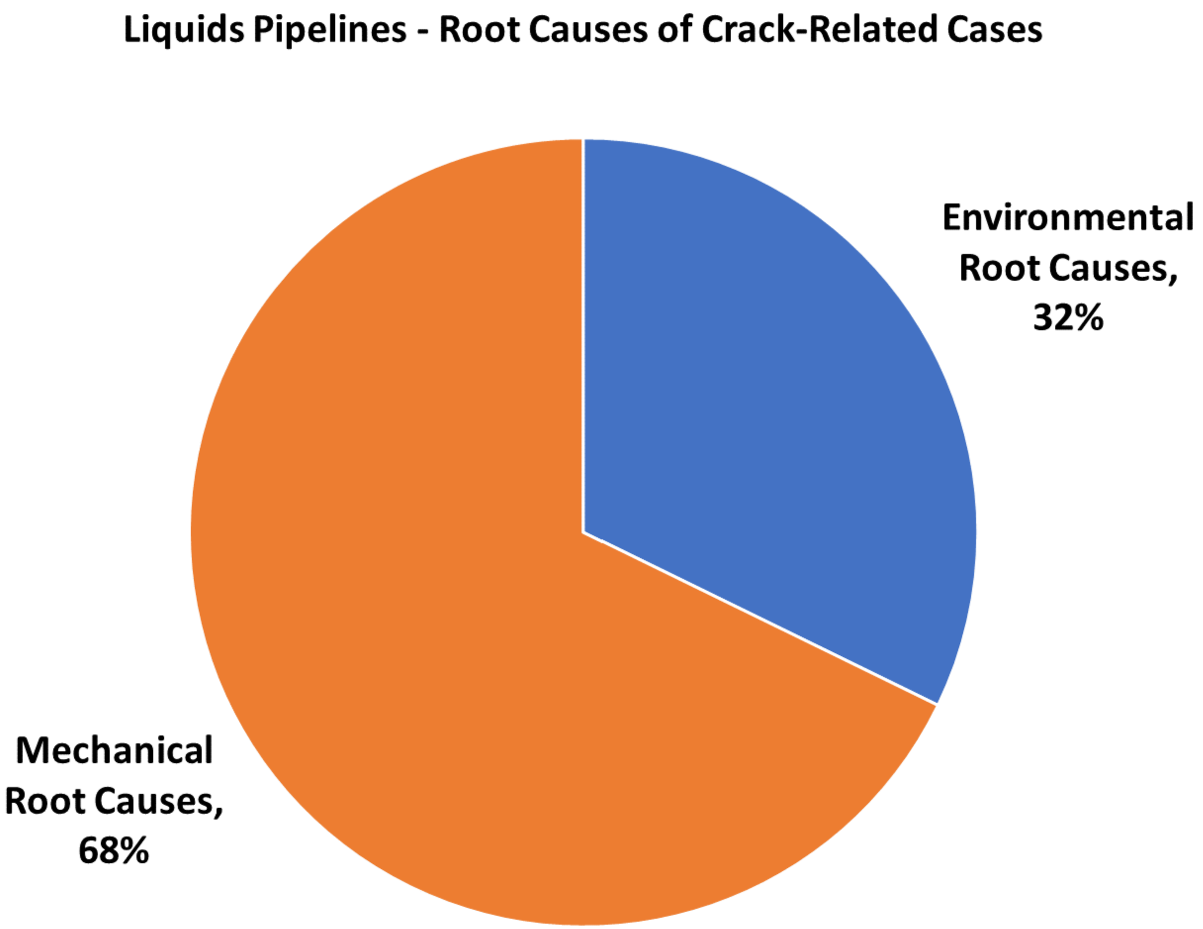
Crack-Related Failures: Discovery Time and Appearance

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**

- The data *showed that far more crack related failures discovered from in-service experience, than form ILI or hydrotesting.*

Crack-Failures by cause in gas lines, liquids lines





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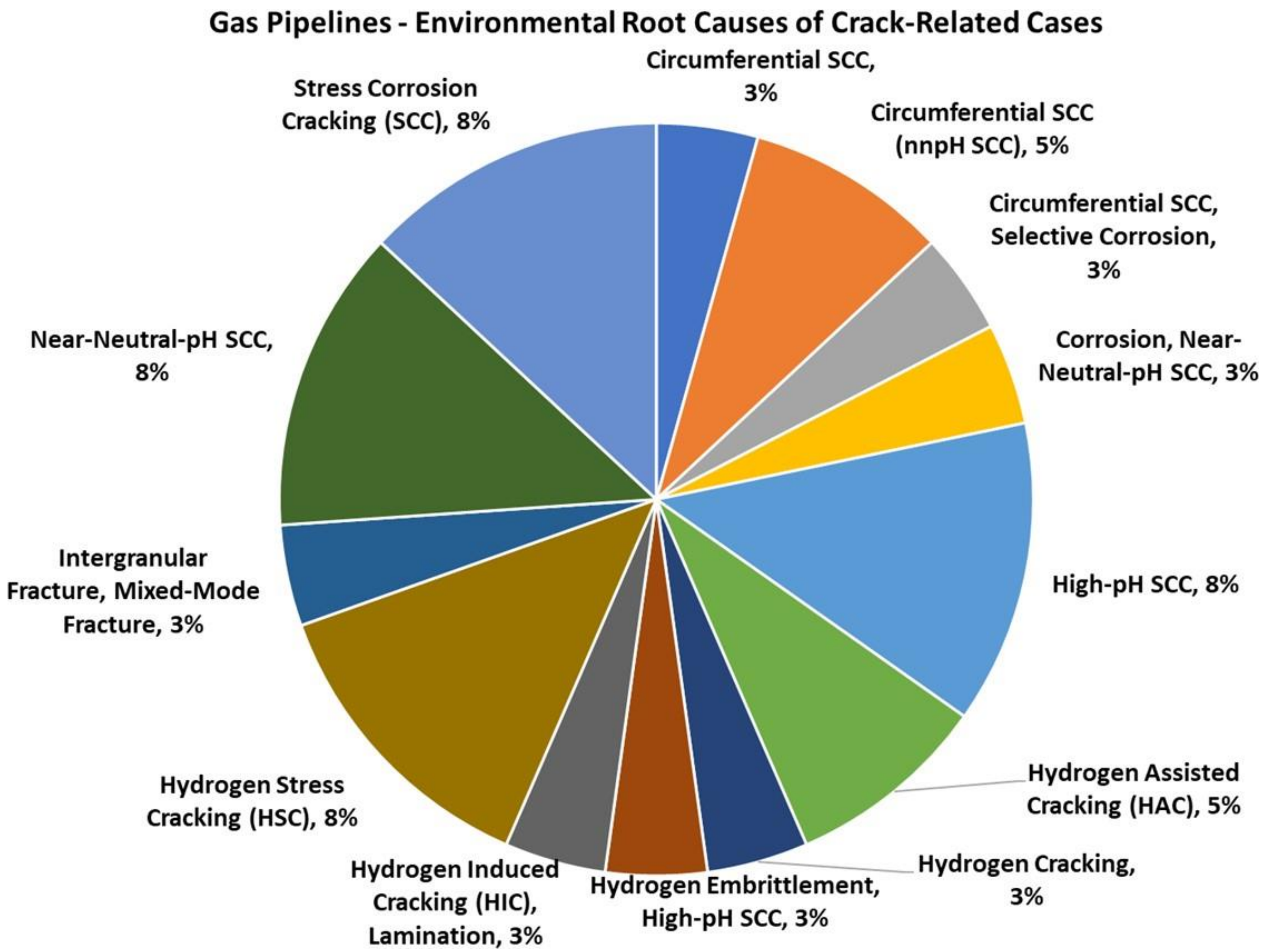
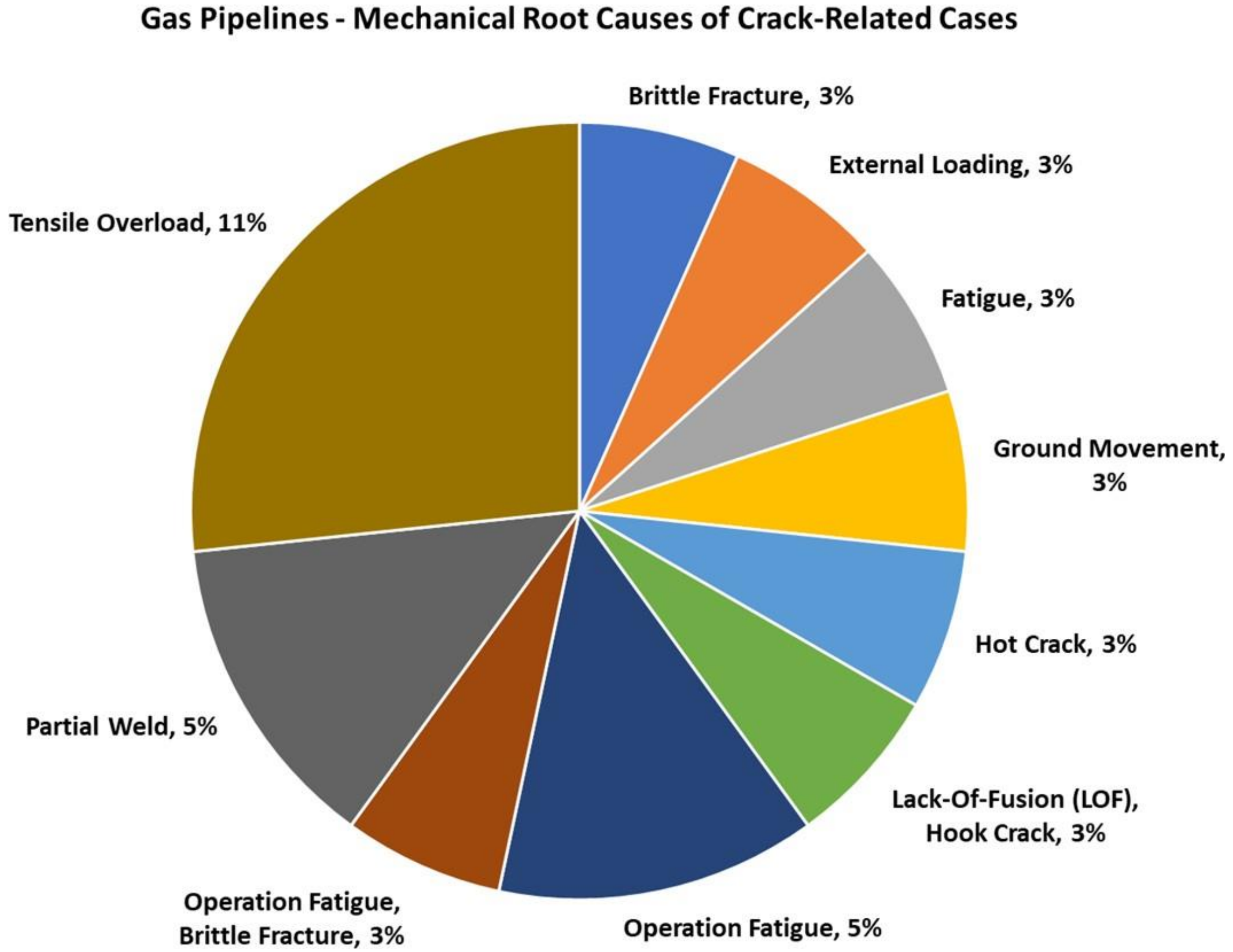
Gas Pipelines – Causes for Crack-Related Cases

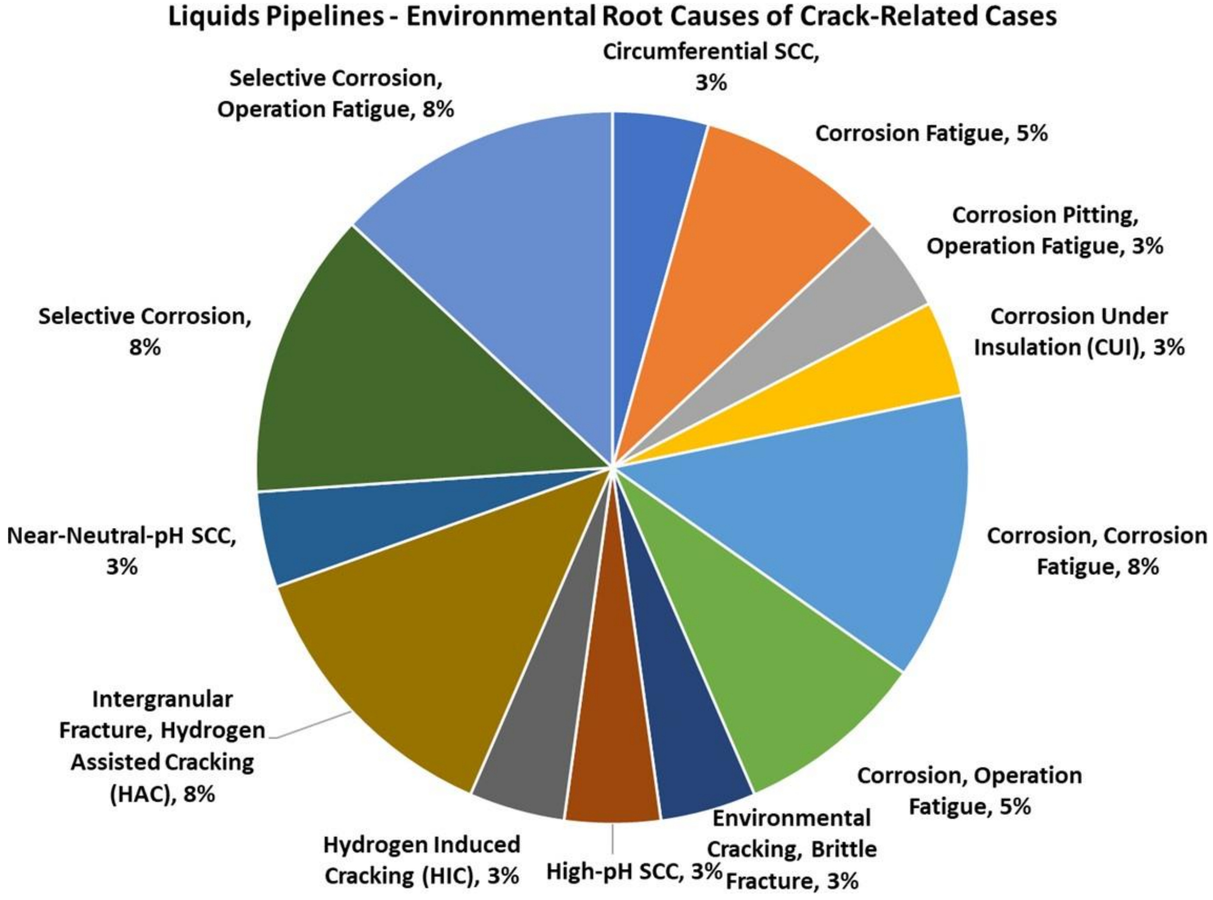




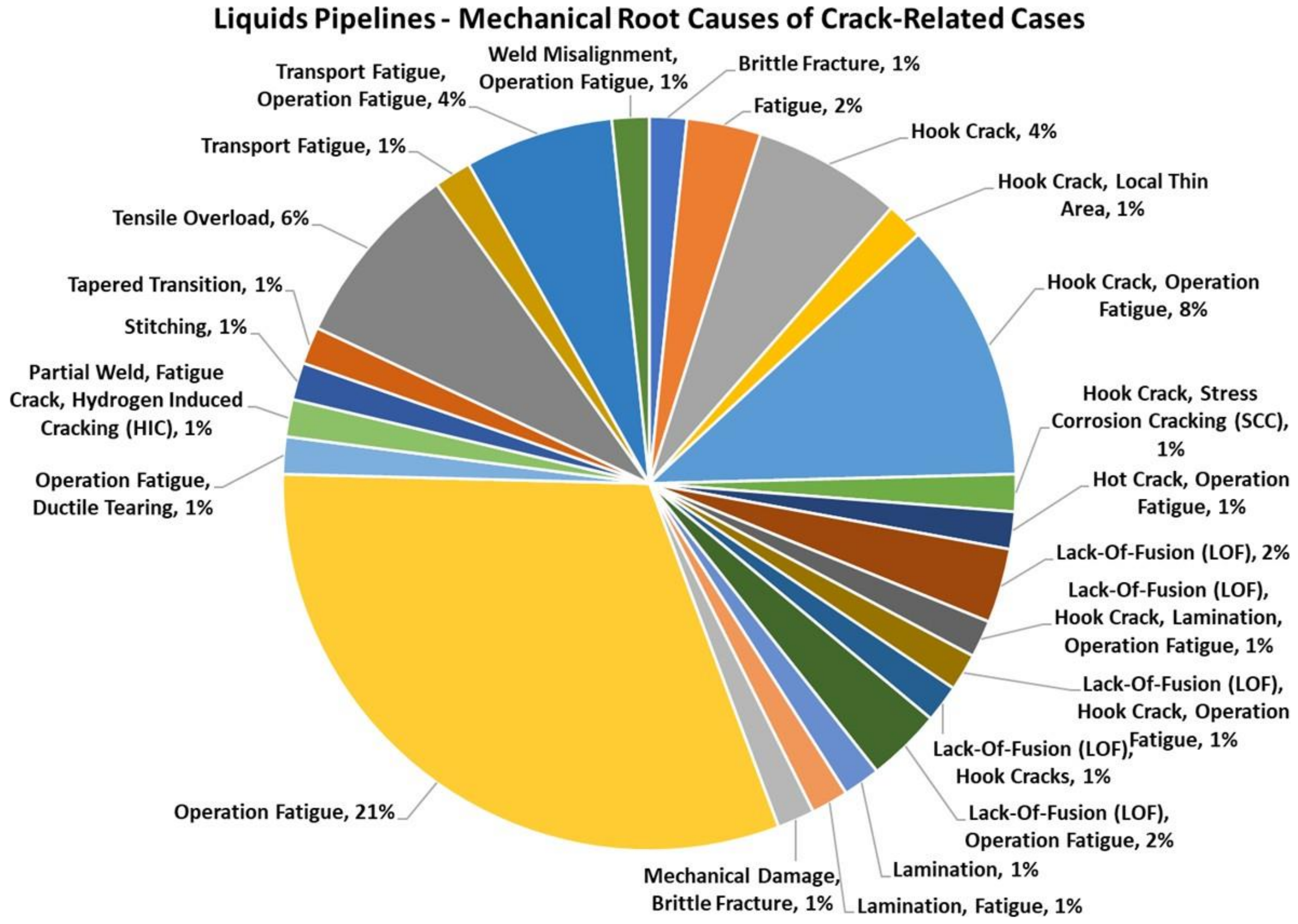
SCC causes ~65%, hydrogen ~35%

Fatigue ~20%, External loads ~30%, manufacturing flaws ~20%, tensile overload ~30%

Liquids Pipelines – Causes of Crack-Related Failures

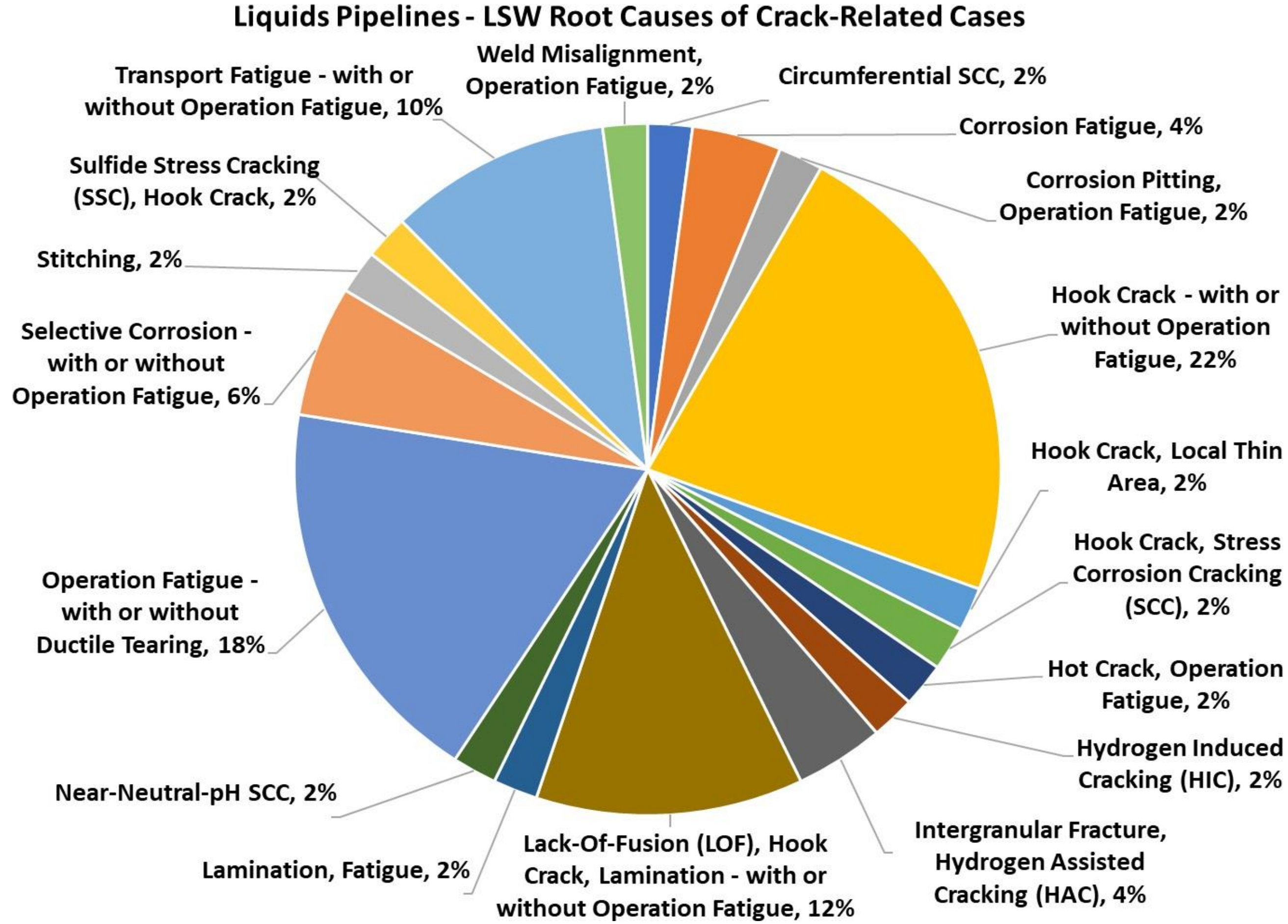


SCC causes ~25%, hydrogen ~20%, selective corrosion/corrosion ~40%, corrosion/fatigue ~15%



Fatigue ~35%, manufacturing flaws ~45%, tensile overload ~10%, other 10%

Crack-Failures at Long-Seam Welds in Liquids Pipelines



SCC causes ~15%, hydrogen ~15%, selective corrosion/corrosion ~20%, manufacturing ~40%

Crack-Related Failures: by CM-SRP pillars

#	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

- PRIORITIZATION: Strictly considering the historic incident root causes, the order of *priority for future research to prevent crack-related failures should be:*

1. Susceptibility, 2. Management, 3. Inspections, 4. Assessment and Remediation.

Research Gaps in Cracking Susceptibility

1. Improve cracking threat assessment methodologies,
2. Perform research to better understand and explore methods to minimize the threat of operational fatigue cracking,
3. Perform research to better understand and explore methods to minimize the threat of hydrogen assisted cracking (HAC) in vintage pipelines,
4. Perform research to establish crack growth rates (CGRs) for SCC,
5. Perform research to update crack interaction rules for SCC,
6. Perform research to determine threshold for crack initiation at selective corrosion,
7. Define what data to collect for a pipeline to determine susceptibility to specific cracking mechanisms,
8. Establish state-of-the-art of existing knowledge about mechanical behavior of linepipe steels exposed to hydrogen environment to enable conversion of vintage pipelines for hydrogen transport, and
9. Develop ILI methods that can non-destructively estimate material properties.

Research Gaps in Inspections for Cracks

1. Develop standard for descriptive terminology for crack-like anomalies,
2. Investigate detrimental versus beneficial effects of hydrostatic testing for liquids pipelines,
3. Investigate detrimental versus beneficial effects of hydrostatic testing for pre-qualifying a pipeline for pure or blended hydrogen service,
4. Collect and manufacture ILI test spools for validation of tools for cracks at welds,
5. Investigate benefits of running multiple <u>different</u> crack detection ILI technologies in the same pipeline,
6. Investigate benefits of multiple runs of the <u>same</u> crack detection ILI tool in the same pipeline,
7. Provide training about line pipe features for field-NDE inspectors and ILI analysts, and
8. Develop an NDE database.

Research Gaps in Assessment and Remediation of Cracks

1. Update the PRCI Pipeline Repair Manual,
2. Investigate influence of data quality and data uncertainties on assessment results,
3. Improve crack-growth-rate data for operational fatigue assessment,
4. Improve modeling of operational fatigue for complicated crack configurations,
5. Perform testing and update the fracture initiation transition temperature master curve model for newer line pipe steels, and
6. Continue improving crack assessment models for girth welds.

Research Gaps in Crack Management

1. Make PRCI research more easily available among PRCI members,
2. Make PRCI research results available beyond PRCI members,
3. Develop standard QA/QC procedures for procurement of new line pipe,
4. Collect and manufacture ILI test spools for validation of tools for cracks coinciding with other damage, and
5. Develop a crack-specific guideline for integrity management programs.

Next Steps for PRCI Members

1. Formalize the 28 research suggestions by submitting them in PRCI web tool
   - Can be entered by committee representatives
2. Perform cross-referencing of new ideas with existing ideas and CM-SRP priorities
   - Final Report provides cross-referencing
3. Prioritize ideas based on PRCI resources
   - Ideas are labeled by technical committees (DMC, I&I, CORR) in the project report
4. Prepare and issue RFPs for future research
   - Detailed idea descriptions are suggested in the project Final Report

Thank you for your attention

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