Pipeline Research Council International

Evaluation of Casing Integrity for Underground Storage Wells

PHMSA Contract 693JK31810014 - Project #747
PRCI Project US-3J

July 7, 2021

Presenters:
Gang Tao, PhD, PEng, C-FER Technologies
Mark Stephens, MSc, PEng, C-FER Technologies

C-FER Technologies
A SUBSIDIARY OF ALBERTA INNOVATES

PRCI™
LEADING PIPELINE RESEARCH

Disclaimer

Project Team

PRCI Team

Andrew Lloyd (Team Lead)	Enterprise Products
Mark Thompson	Enterprise Products
Luke Dewig	TC Energy
Tara Fuchs	TransGas Ltd.
Rocky Halbgewachs	TransGas Ltd.
Ray Harris	National Fuel Gas Supply Corporation
Robert Heine	Williams Companies, Inc.
Larry Kennedy	Pacific Gas and Electric Company
David Xu	Pacific Gas and Electric Company
Robert Kurima	Chevron Pipe Line Company
F. Leeson	Dominion Energy Transmission, Inc.
Mike Olesko	Plains All American Pipeline, LP
Jim Tomlinson	Marathon Pipe Line LLC
Jeff Sutherland	Baker Hughes, a GE company
Zoe Shall (Program Manager)	Pipeline Research Council International, Inc.

C-FER Team

Gang Tao (Principle Investigator)

Mark Stephens

Diana Abdulhameed

Brian Wagg

Problems and Challenges Addressed

- Real performance capability of casing corrosion logging technologies was unclear to UGS operators, and this was experimentally and analytically investigated in the project.
- Accuracy of remaining burst strength prediction models for downhole casing application was unknown, and this project critically reviewed and compared the models.
- A reliability-based framework for casing integrity assessment was developed in this project to provide a better process for casing corrosion management.

Project Objectives

- Improve understanding of corrosion logging tool performance
- Expand corroded casing burst test data set
- Benchmark burst prediction models (against tests and FEA)
- Outline a reliability-based casing integrity assessment framework to support improved decision making with regarding to well interventions and operating parameters

Project Tasks and Funding Support

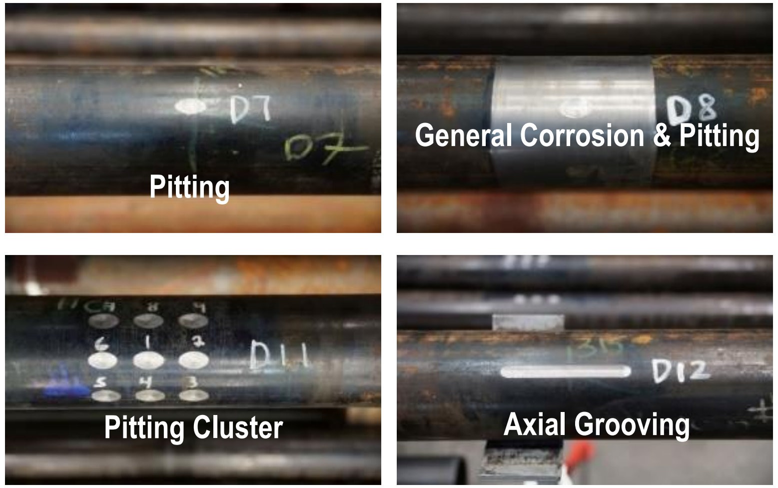
Task No.	Task Description
1	Literature Review (Logging Technologies and Burst Strength Prediction Models)
2	Logging Tool Test and Performance Evaluation (Three Vendor Tools)
3	Physical Burst Test Validation (Twenty Full-Scale Burst Tests)
4	Finite Element Analysis (Test Specimens Under Lab and In-situ Load Conditions)
5	Reliability-Based Assessment of Casing Strength (Framework and Demo Analysis)
6	Reporting, Management and Meetings

- **Total Project Funding: US$415,910**
- **This project was co-funded between PHMSA and PRCI (50/50).**
- **Additional funding was provided by PRCI to support prototype tool development and remote testing (to overcome travel restrictions due to the pandemic).**

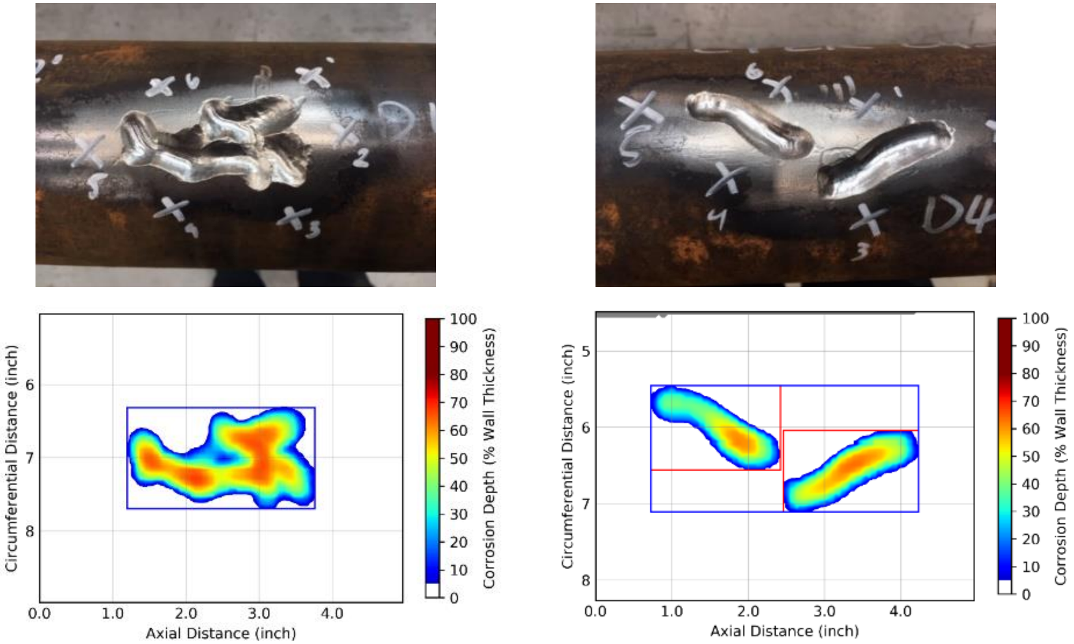
Steps Taken to Address Each Task

- **Improved understanding of casing corrosion logging technologies (Tasks 1 and 2)**
  - Established a better understanding of state-of-the-art in casing logging technologies through literature review (Task 1) and vendor interviews (Task 2).
  - Obtained insight on real performance of selected logging tools by full-scale testing (Task 2).
- **Improved understanding of remaining strength prediction models for downhole casing application (Tasks 1, 3 and 4)**
  - Overview of models based on literature review (Task 1)
  - Statistical evaluation of predictive capability based on full-scale burst test results (Task 3)
  - Investigated local stress/strain response and failure mechanism using advanced FEA (Task 4)
  - Investigated effects of in-situ load conditions (i.e. axial constraint) on burst strength of corroded casing (Task 4)
- **Developed reliability-based framework for casing integrity assessment to provide a better process for casing corrosion management (Task 5)**

Logging Tool Test Evaluation – Specimen Preparation



- Machined regular shape features
- Feature sizes measured by hand



- Hand-formed random shape features
- Features characterized by laser scans
  - Data analyzed using C-FER's in-house feature mapping application

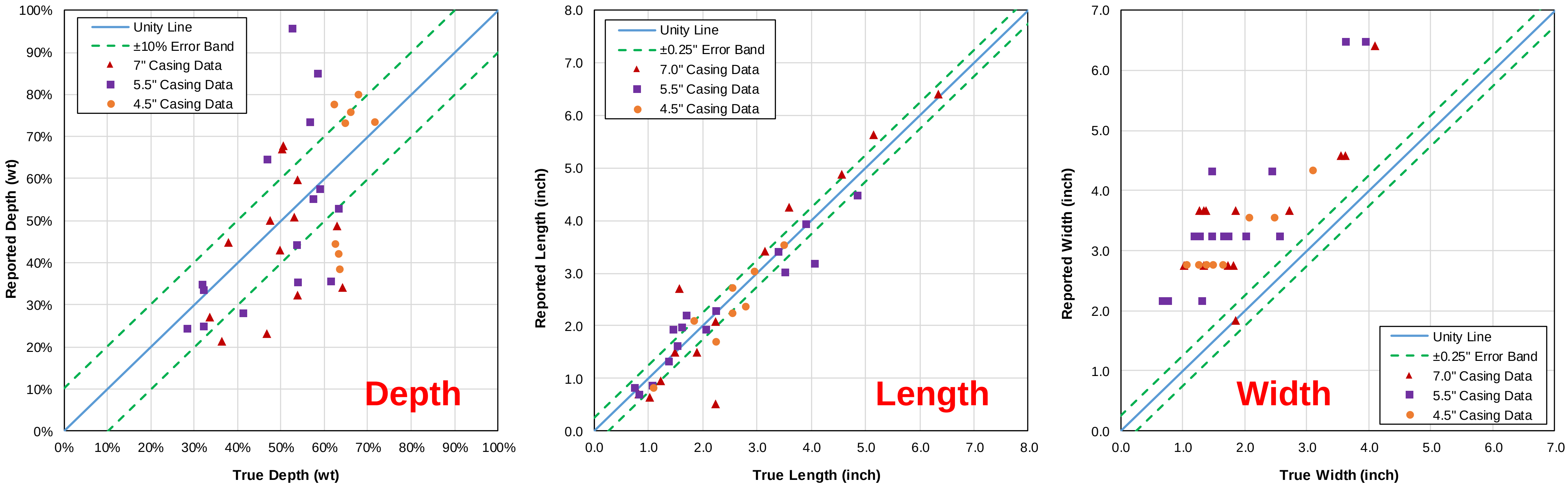
Logging Tool Test Evaluation – Test Execution

Ultrasonic Tool

Magnetic Flux Leakage Tool

Magnetic Eddy Current Tool

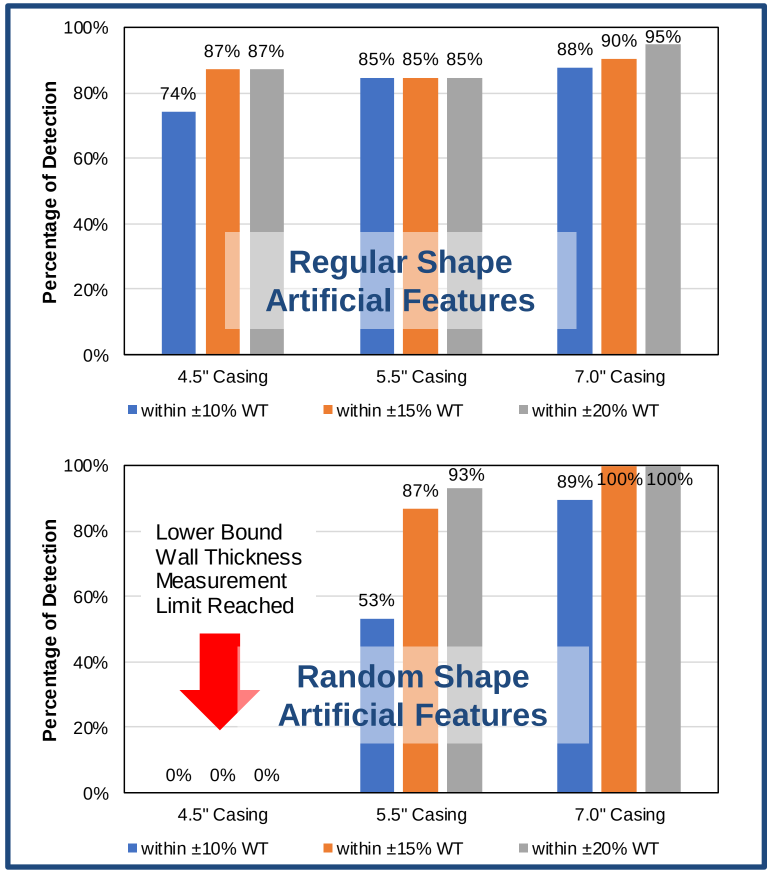
Logging Tool Test Evaluation – Sizing Accuracy



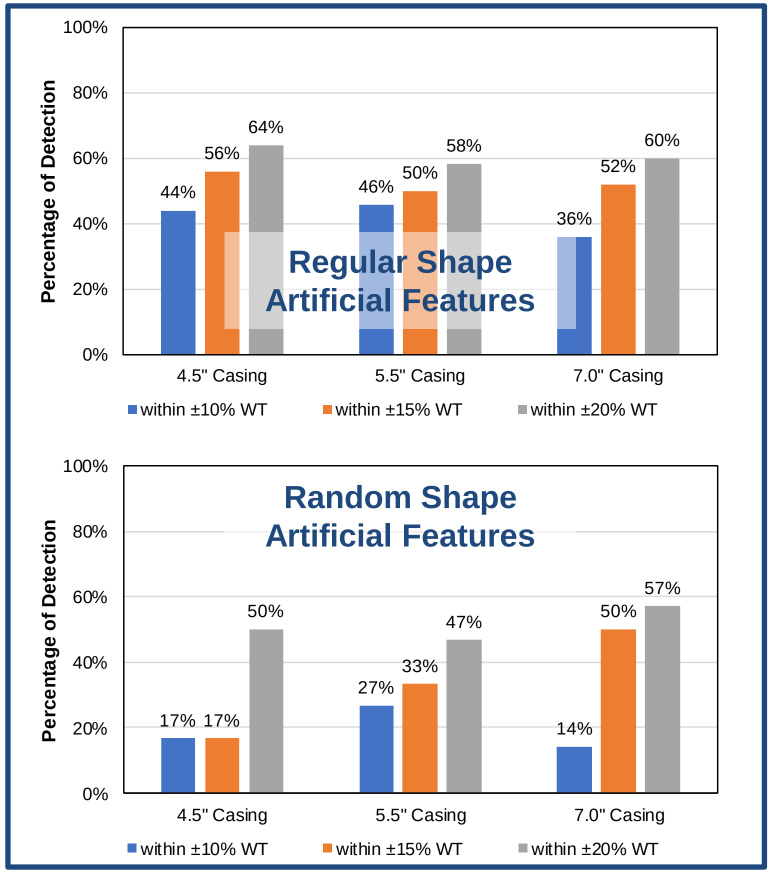
Feature sizing accuracy evaluated using unity plot and error band (an example of the MEC tool on sizing random shape features)

Logging Tool Test Evaluation – Sizing Accuracy

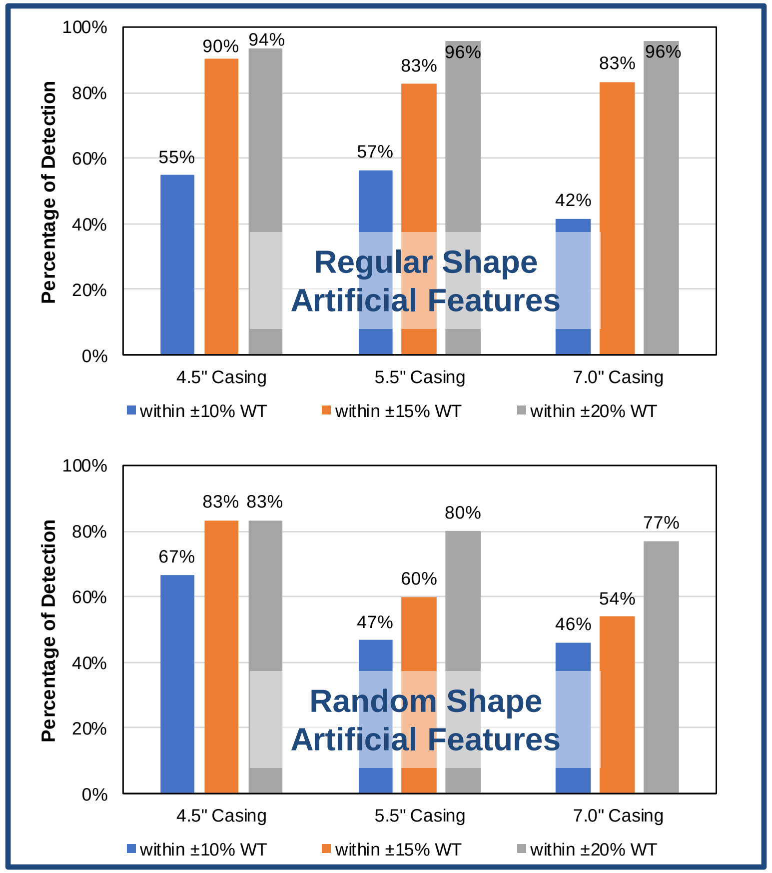
UT



MFL



MEC



Feature sizing accuracy evaluation (an example of depth accuracy)

Logging Technologies – Results Overview

Multi-Finger Caliper (MFC)

- Suitable for well deformation assessment
- Need to be careful about assumptions made for metal loss assessment
- Resolution is limited for small isolated features

Ultrasonic Testing (UT)

- Must have liquid in the well
- Provides direct wall thickness measurement
- Can achieve good accuracy
- Suitable for isolated feature assessment
- Large performance variations between vendors

Magnetic Flux Leakage (MFL)

- Provides relative wall loss measurement
- Can achieve good accuracy
- Suitable for isolated feature assessment
- Large performance variations between vendors

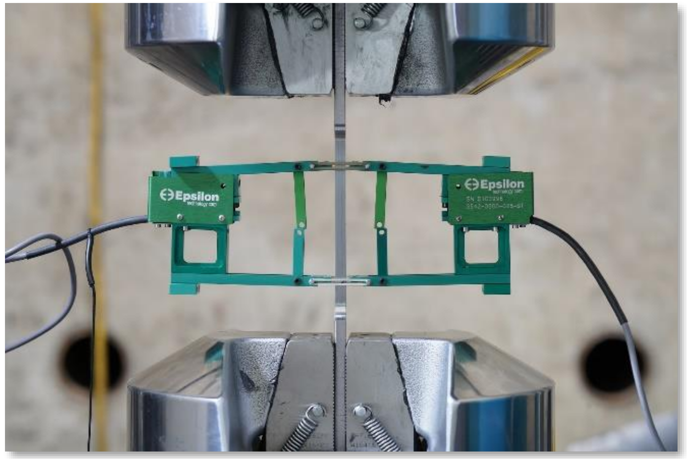
Magnetic Eddy Current (MEC)

- Provides relative wall loss measurement
- Can achieve good accuracy
- Suitable for isolated feature assessment
- Prototype tools soon to be commercialized

Electromagnetic (EM)

- Capable of thru-tubing logging
- Low resolution
- Can only detect average wall loss
- Not suitable for isolated feature assessment
- Need further study to better understand performance capability

Remaining Burst Strength Prediction – Physical Testing



Coupon test

- Rectangular coupons
- ASTM E111 procedure
  - double class B-1 extensometers
  - strict alignment check
- Strain-controlled mode at a constant strain rate of 0.3%/min

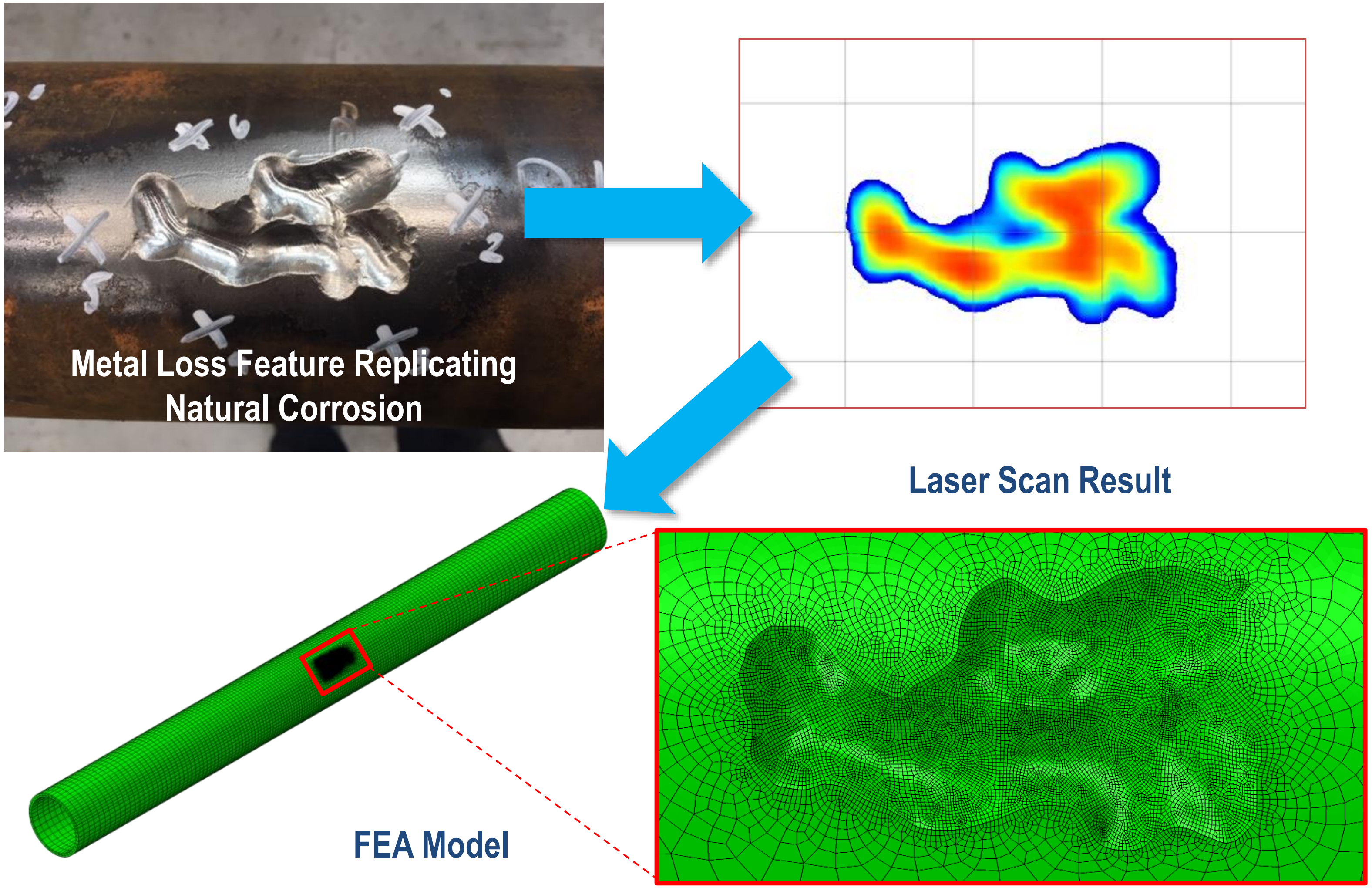
Burst test

- Twenty tests
- Capped-end condition
- Failure as ductile rupture or small leak
- extensive wall thinning and tearing indicating ductile failure mode
- burst pressures in range of 5,000~10,000 psi.

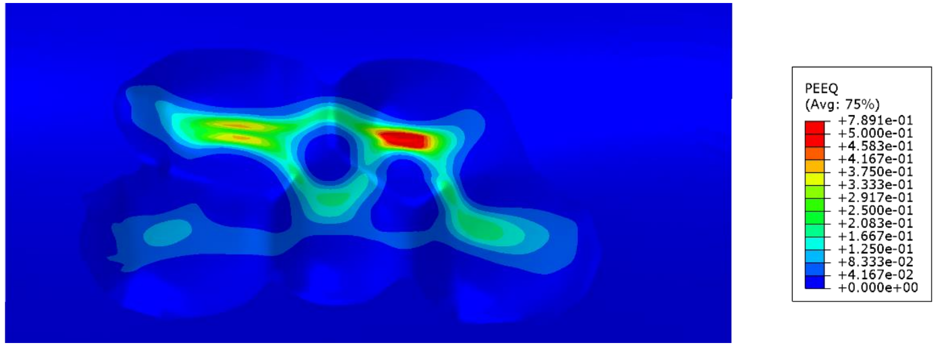
Casing Configuration				Defect Type	Number of Tests
OD (inch)	Weight (ppf)	D/t	Grade		
4.5	11.6	18	J55	Random Shape Artificial Defects	8
5.5	15.5	20			6
7.0	23	22.1			6

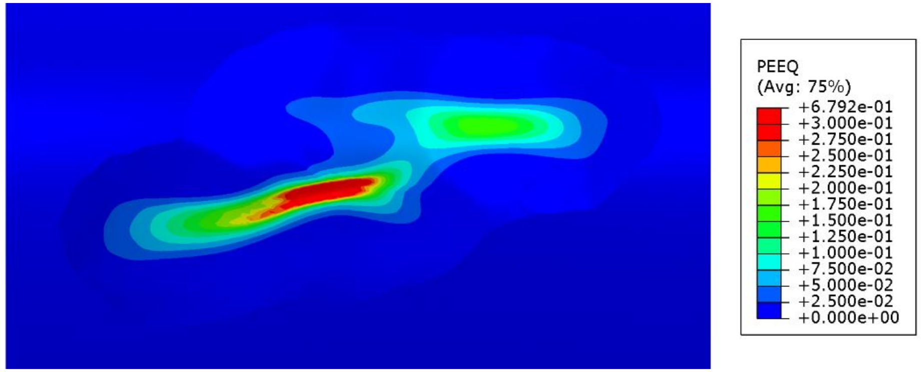
Remaining Burst Strength Prediction – FEA

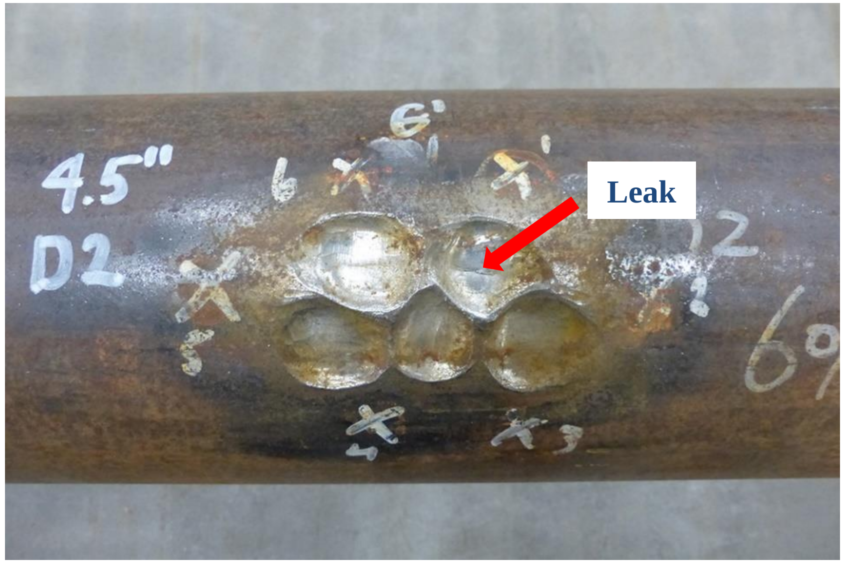
- **Material response from coupon tests**
- **Geometry model based on nominal casing size and actual metal loss profile**
- **Load conditions**
  - Capped-end (lab test condition)
  - Axially constrained (in-situ condition)
- **Failure Criterion**
  - Predictions based on the plastic collapse criterion (plastic instability) exhibited much better accuracy than those based on the von Mises stress within the metal loss.



Remaining Burst Strength Prediction – FEA

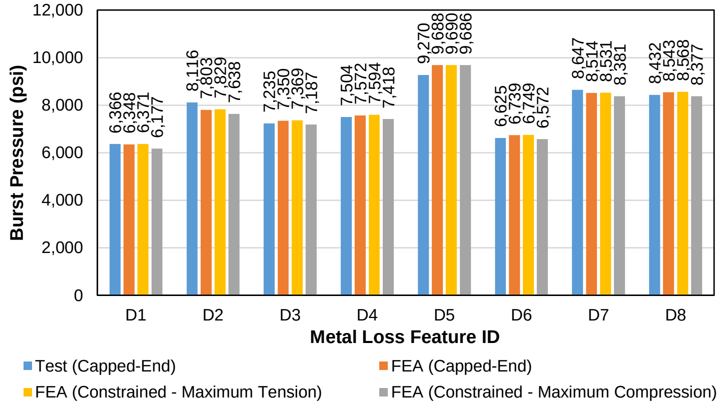




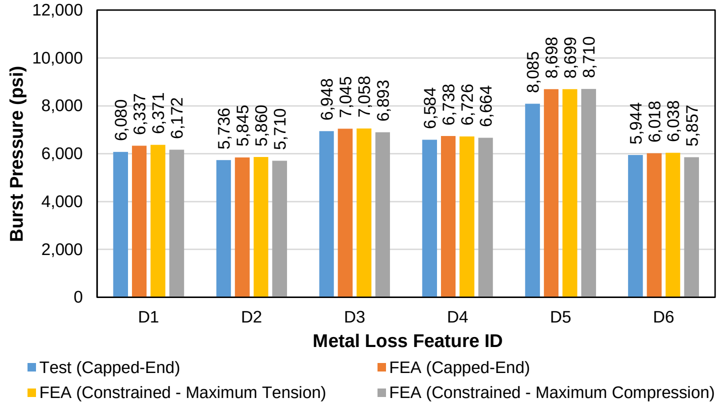


Excellent prediction of the failure location by FEA

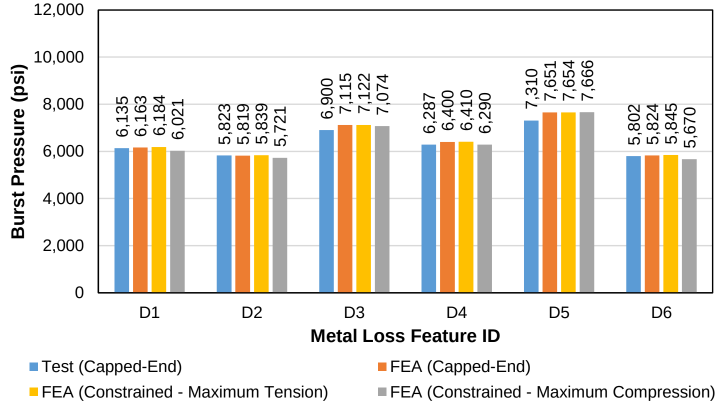
Remaining Burst Strength Prediction – FEA



4.5 inch Casing



5.5 inch Casing

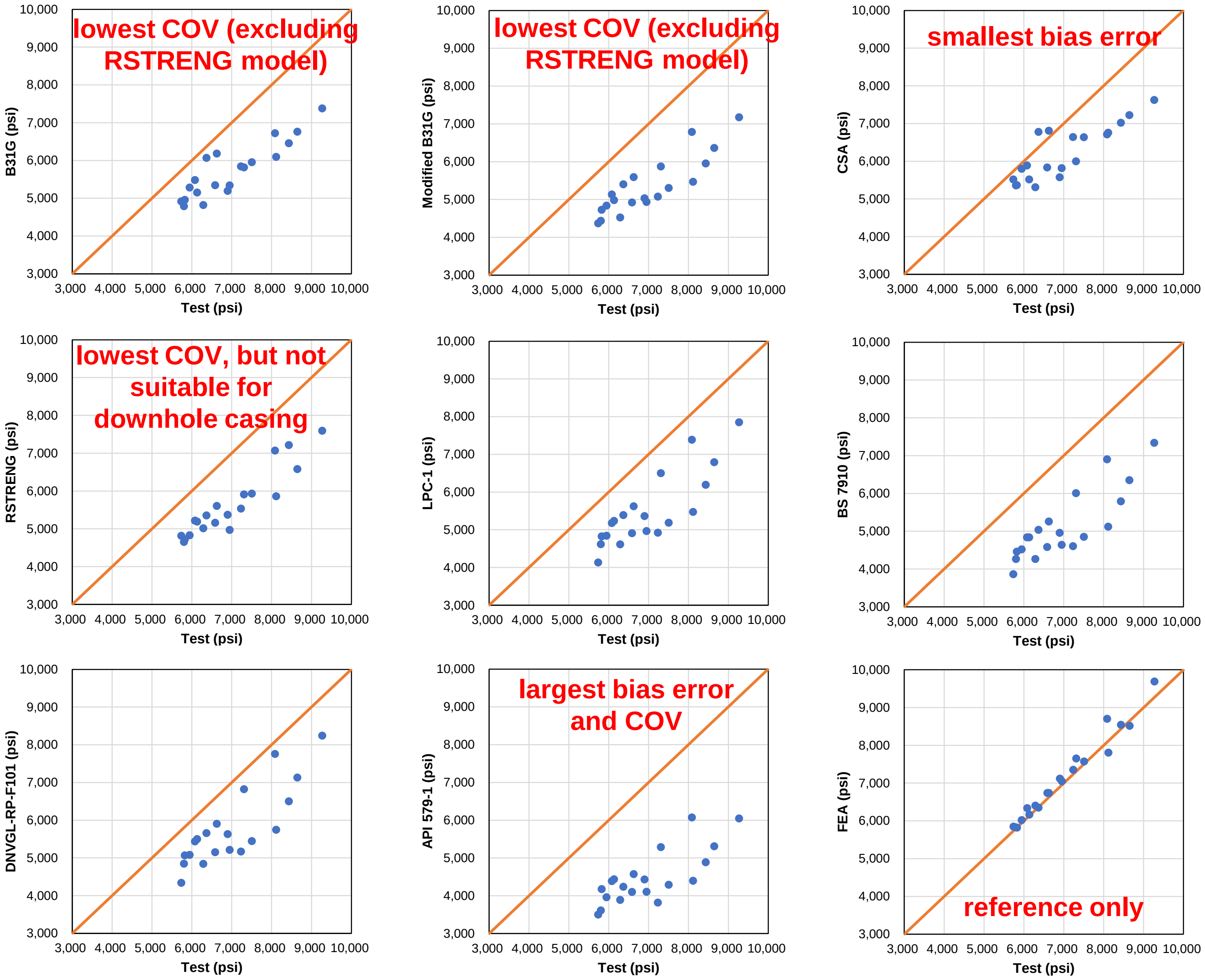


7.0 inch Casing

- **FEA models were validated by excellent prediction accuracies in both burst pressure and failure location for the twenty burst specimens.**
- **Burst failure mechanism of the twenty specimens was shown to be dictated by plastic collapse (plastic instability) rather than the von Mises stress alone. Material ductility and post-yield stress-strain relationship play key roles in the remaining burst strength.**
- **Axial constraints (e.g. cemented casing) showed minimal impact on remaining burst strength in FEA.**
  - The locked-in axial compressive strain caused a marginal reduction in burst strength.
  - The locked-in axial tensile strain had a negligible impact on the burst strength.
  - A similar finding was reported in a previous US DOT PHMSA project for line pipe specimens with FEA and full-scale test evidence (DTPH56-14-H-00003, Project #556).

Remaining Burst Strength Prediction – Model Evaluation

- Predictive capability of various models was evaluated against physical burst test data.
- Actual YS and UTS were used instead of SMYS and SMTS in the calculation.
- FEA predictions also included for comparison
- All analytical models underestimated capacity by between 10% to 36%.
- Bias error can be corrected with a multiplicative factor, and COV (coefficient of variance) reflects the scatter and is a critical measure of model prediction capability.

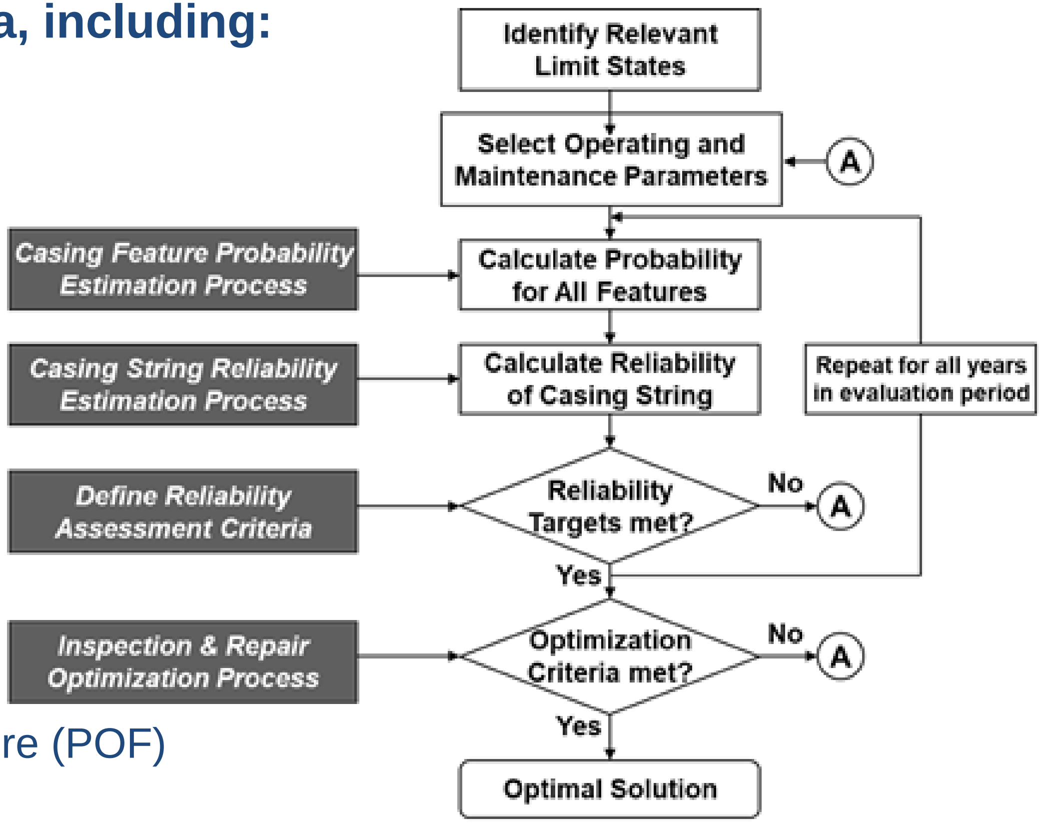


Remaining Burst Strength Prediction - Conclusions

- **Remaining burst strength prediction models implicitly include the D/t parameter in the Folias factors. Prediction models calibrated based on large D/t line pipe samples may not be readily suitable for smaller D/t casing samples.**
- **Further development of remaining burst strength prediction models for downhole casing applications is warranted.**
  - Eliminate the excessive conservatism in burst strength calculations
  - Further development of advanced models considering strain hardening property of casing materials
- **Some existing methods to account for axial load effects (e.g. in-situ load condition) on casing burst strength are questionable, and further investigation is needed.**

Reliability-based Casing Strength Assessment

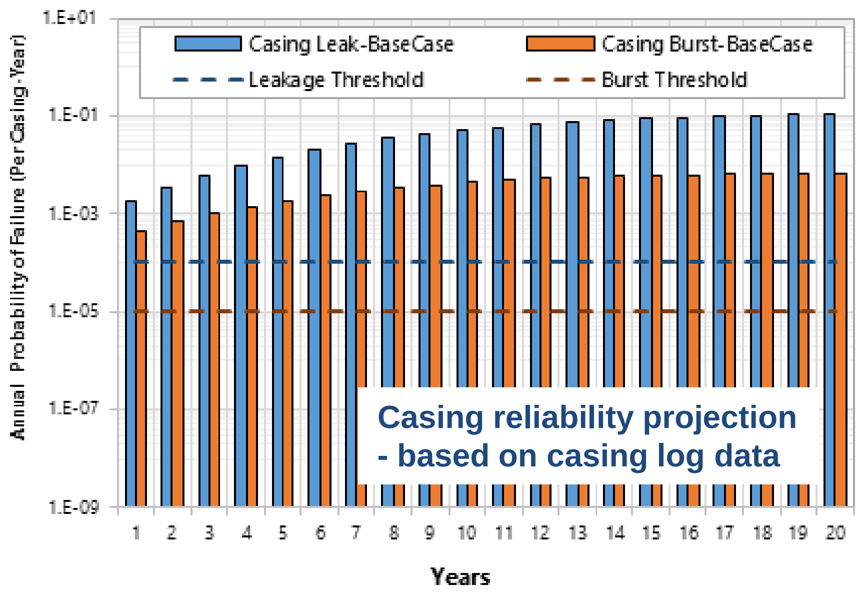
- **Reliability-based framework developed to address issues pertinent to casing corrosion management based on integrity log data, including:**
  - defect-specific probability estimation;
  - the treatment of inspection-related uncertainties;
  - appropriate measures of casing reliability;
  - the basis for reliability assessment criteria; and
  - the relationship between:
    - measured casing damage severity;
    - the required extent of repair and time to next inspection

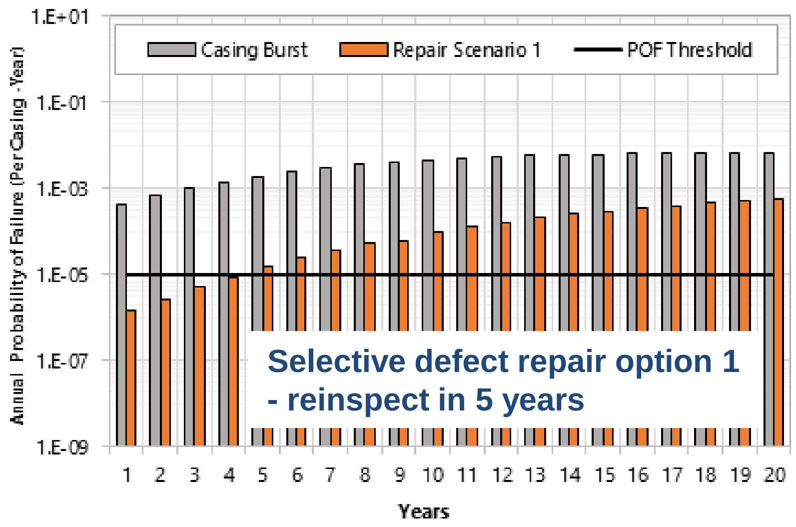


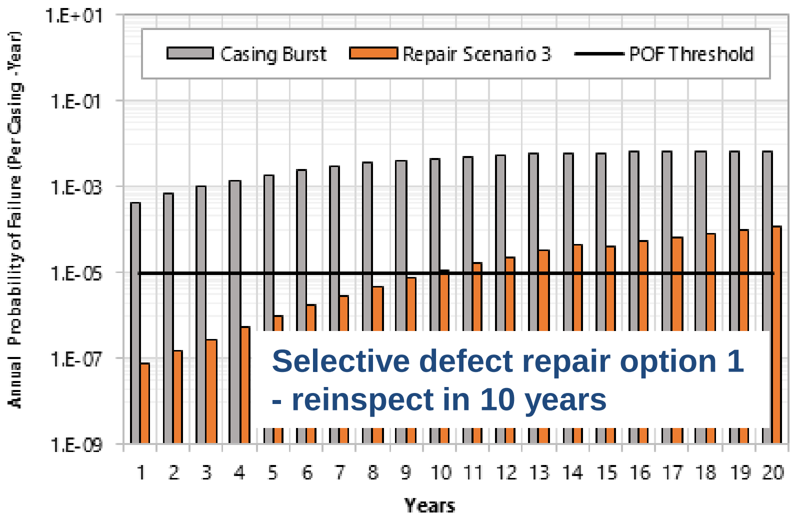
- **Why develop a 'probabilistic' framework?**
  - Deterministic - safety margin <u>implicitly</u> controlled by conservative input assumptions and chosen safety factor (SF)
  - Probabilistic - safety margin <u>explicitly</u> controlled by defined input uncertainties and chosen limit on probability of failure (POF)
    - POF thresholds can be chosen to achieve safety and/or environmental risk consistency

Reliability-based Casing Strength Assessment

- **Framework application illustrated with analysis of hypothetical casing string to show:**
  - how casing log data (and inspection tool accuracy characterization) can be used to estimate casing reliability as a function of time;
  - how selected corrosion feature remediation affects the reliability projections; and
  - how results can be used to support the determination of the required time to next inspection.







Recommended Future Research

Improvement of Casing Corrosion Logging Technologies

- Expand lab test dataset of high-resolution logging tools (e.g. to quantify sizing uncertainties)
- Develop a downhole corrosion logging system qualification guideline
- Evaluation and improvement of through-tubing logging tools

Improvement of Remaining Burst Strength Prediction Models for Downhole Casing

- Additional burst tests considering a broader range of metal loss features, other casing grades and axially constrained condition
- Additional FEA (e.g. a greater variety of metal loss features, casing configurations and in-situ load conditions) to supplement lab tests
- Improve existing prediction models
- Additional investigation of burst strength of vintage casing
- Investigation of strain rate impact on casing remaining strength

Recommended Future Research

Further Development of Reliability-based Casing Corrosion Management Framework

- Develop consensus-based casing reliability thresholds (maximum allowable probability of casing failure) with consideration of consequences of failure
- Incorporate considerations for balancing the risk reduction achieved by casing feature remediation and/or re-inspection against the risk increase associated with additional well entry (see PHMSA report "Risk Assessment and Treatment of Wells")

Identification and Mitigation of Other Downhole Threats

- Further research is recommended to identify and better understand additional downhole threats that may compromise casing integrity in UGS wells (e.g. environmental assisted cracking, casing deformation, long-term casing connection sealability and structural integrity)
- Investigation of cement integrity issues and remediation methods

Technology Transfer

- A final technical report was submitted to PHMSA.
- Interim project results have been presented and discussed at PRCI UGS Technical Committee meetings (twice a year) throughout the project life.
- A presentation on the evaluation results of download casing corrosion logging tools has been presented in the 2021 PRCI Research Exchange Meeting.
- Findings from this research project will be published in journals and/or industry conferences.
- A technical workshop will be scheduled in late 2021 to present the technical details of this project. The workshop will be organized by PRCI and will be freely accessible to all registered industry participants.
- Key findings of this research could have the potential to be implemented into future industry best practices or standards (for UGS or general well integrity).

Project Documents

The project final report and this presentation are available for public download from PHMSA website:

https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=747

Project Contact

For any enquires about this project, please contact:

Gang Tao, PhD, PEng
Senior Research Engineer
C-FER Technologies (1999) Inc.
Direct: 1.780.450.8989, ext. 311
Cell: 1.780.782.9407
g.tao@cfertech.com
www.cfertech.com

Zoe H. Shall
Program Manager, Integrity and Inspection and Underground Storage Committees
Pipeline Research Council International
Office +1-571-600-2001 x104
mobile +1-402-680-9186
zshall@prci.org
www.prci.org

Acknowledgement

We would like to sincerely acknowledge the contributions from all parties involved in this research program.

- **Funding support from PHMSA and PRCI**
- **Support and technical advice from members of the underground storage technical committee at PRCI**
- **Direction and oversight from Ms. Zoe Shall at PRCI throughout the execution of this program**
- **Participation of logging service vendors in the test program and contribution of their valuable knowledge towards this research project**

Pipeline Research Council International

LEADING PIPELINE RESEARCH

THANK YOU FOR JOINING THIS PRESENATION